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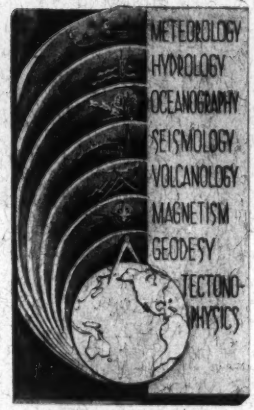

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SOME ASPECTS OF GEOPHYSICS IN CANADA WITH SPECIAL REFERENCE TO STRUCTURAL RESEARCH IN THE CANADIAN SHIELD

(Part 1: Review of recent geophysical work in Canada)

J. Tuzo Wilson

Abstract--After mentioning how the National Committee for Canada of the International Union of Geodesy and Geophysics has been reorganized, this paper reviews recent progress in geophysics in Canada. Both routine and research work are discussed in the fields of geodesy, gravity, meteorology, hydrology, oceanography, seismology, terrestrial magnetism, atmospheric ionization, radioactivity, geothermometry, volcanology, and tectonics. A hundred references are given to Canadian papers, most of which have appeared since the end of the War.

Introduction

It is the object of this paper to present a brief review of research and organization of geophysics in Canada. While it can not hope to be complete, an attempt has been made to select sufficient examples of work now in progress to show that recently there has been great activity and expansion. Canadian journals may be obscure to some and in any case their publication was interrupted by the War so that an effort has been made to include references to as many recent Canadian papers as possible. A few papers several years old have been included where their results seemed important and have not been superceded.

National Committee for Canada of the International Union of Geodesy and Geophysics

The Dominion Government has long been active in geophysical work and so, more recently, have Canadian companies and universities, but the War led to very great increases which are likely to be maintained in order to meet the demands of air transportation, of mining, and of the oil industry.

For many years the Department of Mines and Resources has supported a National Committee for Canada of the International Union of Geodesy and Geophysics of which Noel J. Ogilvie and C. H. Ney have latterly been Chairman and Secretary, respectively. Before the War it was particularly active in the fields of geodesy, gravity, terrestrial magnetism, and seismology.

In Canada, as in the United States, oil companies extensively use seismic, gravitational, and magnetic methods of prospecting while the use of magnetic and electric methods of prospecting has been developed more slowly to locate metallic ore bodies so that geophysical prospecting is now a minor industry in which many Canadian companies engage. The war-time development of airborne magnetic instruments promises to increase the speed and value of one of these methods. In 1945, realizing these possibilities, the National Research Council of Canada set up an Associate Committee on Geophysics to develop airborne magnetometers and undertake fundamental research in allied fields. This Committee expanded its interests into geodetic, gravitational, seismic, tectonic, and ionospheric research. The slight overlapping that occurred with the older committee was quickly settled by an amicable and complete combination of the two bodies. By functioning domestically as an Associate Committee of the National Research Council of Canada (corresponding somewhat to a Division of the National Research Council of the United States) the Committee will have increased power to recommend grants for research and pay some traveling expenses; on the other hand, the same committee will exercise international functions as National Committee for Canada of the International Union of Geodesy and Geophysics. Noel J. Ogilvie and C. H. Ney will continue to be active as Honorary Chairman and Honorary Secretary of the combined Committee while the author and Ralph Bailey, Physics Division, National Research Council of Canada, are Chairman and Secretary, respectively.

The work of reorganizing the sections is in hand and so far sections have been established as follows:

Section	Chairman	Secretary
Geodesy	A. H. Miller, Chief, Division of Gravity, Dominion Observatory	C. H. Ney, Chief, Division of Triangulation, Geodetic Service of Canada
Seismology	E. A. Hodgson, Chief, Division of Seismology, Dominion Observatory	W. G. Milne, Dominion Observatory
Meteorology and Hydrology	A. Thomson, Controller of Meteorology, Dept. of Transport	
Terrestrial Magnetism	D. A. Keys, Vice-President, National Research Council	R. G. Madill, Chief, Division of Terrestrial Magnetism, Dominion Observatory
Atmospheric Ionization	F. T. Davies, Chief, Radio Propagation Laboratory, Ottawa	J. H. Meek, Radio Propagation Laboratory, Ottawa
Tectonics	George Shaw, Geological Survey of Canada	

The two sections of Terrestrial Magnetism and Atmospheric Ionization correspond to one international association, but the division was found necessary to meet the requirements of those interested in prospecting and in ionospheric research, whose interests are so different, although their subjects are fundamentally connected.

Other sections will very probably be added as those interested in other fields can be brought together to decide their own requirements. Canadian oceanographers already have a joint Committee which has expressed interest in the formation of a section.

No journal is contemplated other than an annual report [see "References" at end of paper, General: ASSOCIATE COMMITTEE ON GEOPHYSICS, 1947] and a quarterly annoted bibliography for Canadian geophysicists, whose publication was started this year by National Research Council. It is known as The Canadian Geophysical Bulletin [General: CANADIAN GEOPHYSICAL BULLETIN, 1947].

Since 1946 there has also been a Geophysics Committee of the Geology Division of the Canadian Institute of Mining and Metallurgy. This Committee, which has chiefly dealt with legal, financial, and professional matters, has requested changes in customs duties, and in mining assessment laws. The first chairman, T. Koulomzine, has just been succeeded by A. A. Brant.

Geophysical Research in Canada

From the point of view of much geophysical research the Arctic regions are the most interesting and have been the most neglected parts of North America [General: ARCTIC INSTITUTE OF NORTH AMERICA, 1946]. Unfortunately such work often receives more attention because of political implications and because of occasional accidents than on account of the great importance of scientific observations in those regions. Fortunately attention to scientific work there is now greatly increasing, for it is becoming realized that the geographical and magnetic poles and the maximum auroral belt are physically as interesting and worthy of study as is the cold which is more popularly associated with the Far North.

Geodesy--The Geodetic Service of Canada has been active in northern Canada in providing control for mapping that is rapidly being extended to cover the whole mainland part of Canada by use of air photographs. The retiring Director of that Service, N. J. Ogilvie, was also Chairman for many years of the National Committee for Canada of the International Union of Geodesy and Geophysics and an active member of the American Geophysical Union. In many papers he and his staff have kept these bodies well informed of Canadian work [Geodesy: OGILVIE, 1939 and 1946; MONTGOMERY, 1947 and 1948; MILLER, 1946], so that it will not be necessary to add anything except a statement of unpublished isostatic work by the Geodetic Service which F. A. McDiarmid has been kind enough to prepare, as follows:

To date there have been determined the values of the deflection of the vertical in both the meridian and prime vertical at some 300 points in Canada. Most of these stations are in the

Maritime Provinces, Quebec, and Ontario, with comparatively few in western Canada. The deflection of the vertical varies greatly, ranging from practically zero to a maximum of 20".27 at Cap Madeleine on the north coast of the Gaspé Peninsula. It may be pointed out that the observations at the stations on the Gaspé Peninsula, on the St. Lawrence and Bay of Chaleur sides, are most interesting as regards the effect of the attraction of land masses on the plumb. All the stations on the St. Lawrence side show large deflections in the meridian with the astronomical latitude exceeding the geodetic by an average of 15 sec, while those on the Bay of Chaleur side show average deflections of nine sec, with the geodetic latitude larger than the astronomic.

These values of the deflection of the vertical have been corrected for topography and isostatic compensation according to the Hayford and Bowie formula, outlined in the United States Coast and Geodetic Service publications. While in most cases these corrections have reduced the anomalies, yet there are still large unexplained differences. These may be caused by large and hidden masses of extra densities lying beneath the surface.

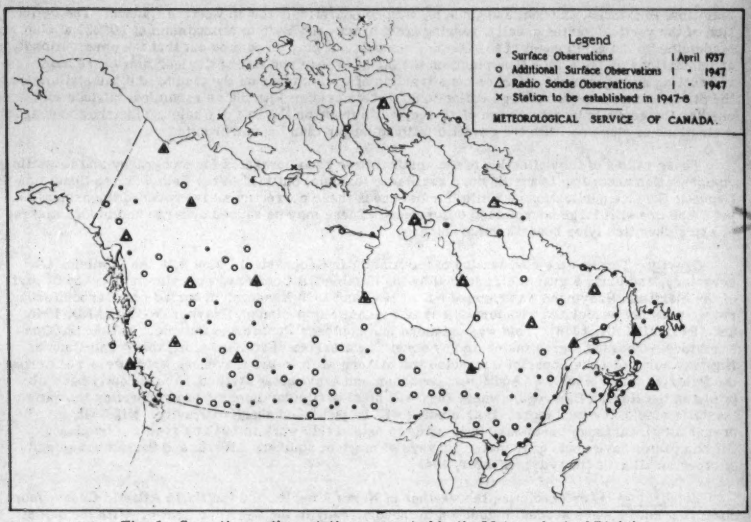
Gravity--Through the cooperation of the American Geophysical Union with the Dominion Observatory, and using a gravimeter loaned by the Humble Oil Company, a gravimeter survey of part of the Maritime Provinces was carried out in 1944 and 1945 in search of buried pre-Carboniferous ridges possibly associated with formations of economic importance [Gravity: WOOLLARD, 1945 and 1946; MILLER, 1946]. This was extended into southern Quebec and Ontario. In 1946 the Observatory purchased a gravimeter and by observing a series of stations along the Trans-Canada Highway north of Lake Superior connected the eastern work to two traverses which were run across the Prairies to the Rockies. Additional pendulum and gravimeter stations have recently been obtained in the Hudson Bay region where they will be of particular interest in interpreting the rapid isostatic rise of the land there. Both studies will be published shortly [Gravity: MILLER, in preparation]. Arrangements have been made to extend this work in 1947 by road and by plane. Oil companies have made gravimeter surveys of much of southern Alberta and Saskatchewan and of other small ares [Gravity: BRANT, 1945].

Meteorology--For predicting the weather of North America and the North Atlantic Ocean, more observing stations are needed in addition to those already in the Canadian Arctic. With the object of assisting this the United States Government in 1946 voted two and one-half million dollars to build weather stations (see bill concerning the establishment of meteorological stations in the Arctic regions, etc., 79th Congress, 1st session, S675, Calendar 659, 1945). Perhaps largely because the Canadian Government had recently paid 100 times that sum to the American Government for work done in northern Canada by the United States Government during the war on Alaska Highway and on northern airfields, the Canadian Government did not agree but instead arranged that it would establish Canadian stations in 1947 with American transportation, and aid of personnel and material, at least in the initial stages. These weather stations have now been established in Victoria, Ellesmere, and Cornwallis Islands, and a few others are intended (see Fig. 1).

The fact that these stations had not been established sooner should not be taken to mean that the Canadian Government is not aware of meteorological needs. It has been rapidly increasing the number of Canadian weather stations in the nearer Arctic and sub-Arctic and otherwise increasing its service. This year's expenditure of four to five million dollars is about ten times as great as that of ten years ago. Per capita it is three times that of the United States. The 19 stations so far established to study upper air conditions are of especial value to the United States. In winter the stations in northwestern Canada help in forecasting outbreaks of polar air which are of vastly greater economic concern to the United States than to Canada, where the winter is cold in any case. This expansion is illustrated in Figure 1, which shows synoptic weather stations operated by the Meteorological Service of Canada. Stations used in preparing $07^{h}00^{m}$ EST forecast on April 1, 1937 are shown together with additional stations used on corresponding forecast ten years later. Stations failing to report and minor changes in location are not shown. The most northerly of the projected stations started operating in April 1947 as a rawinsonde station.

Although these stations are primarily for the purpose of improving forecasting, other research is in hand at the Meteorological Service which is published by members of the staff in numerous articles and books as well as in official documents. Universities and the Ontario Research Foundation are carrying on limited amounts of research especially in climatology. Only selected papers by Canadians are given in the references [Meteorology: all entries]. The importance of all these endeavours was recognized when the Technical Commissions of the International Meteorological Organization met in Toronto in August and September 1947.

Hydrology--Hydrology is being organized for the present as a joint section with Meteorology. Although considerable hydrological work is being done it is scattered among many agencies. The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METEOROLOGICAL SERVICE OF CANADA.

Fig. 1--Synoptic weather stations operated by the Meteorological Division, Department of Transport, Canada

Dominion Government, several provinces, and some transportation and power companies maintain engineers or bureaus that study water supply and resources, irrigation, ground water, flood control, water power, snow removal, ice breaking, snow properties, and allied subjects [Hydrology: DOMINION WATER AND POWER BUREAU, 1947; KERRY, 1946; MACKAY, 1944 and 1945]. These organizations include the Dominion Water and Power Bureau, Department of Agriculture, Geological Survey of Canada, Prairie Farm Reestablishment Administration, National research Council of Canada, National Harbours Board, Quebec Streams Commission, Quebec Department of Lands and Mines, Ontario Department of Mines, Ontario Department of Planning and Development, Research Council of Alberta, Natural Gas Conservation Board of Alberta, Controller of Water Rights for British Columbia, Hydro-Electric Power Commissions of Ontario and Quebec, Shawinigan Water and Power Company, Canadian Pulp and Paper Association, Canadian National Railway, Canadian Pacific Railway, provincial Departments of Highways, and others. Canadians participate in the activities of the Section of Hydrology of the American Geophysical Union and the Western Snow Conference [Hydrology: FARROW, in preparation].

New and important studies on the properties of snow and ice have been undertaken by the Associate Committee on Soil and Snow Mechanics of the National Research Council of Canada. Much unpublished experimental work has been done. Switzerland, England, the United States, and Canada have been visited by members of the Committee in search of data. The results of all this work are now being prepared for publication in a monograph on "Properties of Snow and Ice" by R. F. LEGGET [Hydrology: in press], the Chairman of the Committee.

The Committee arranged for quantitative measurements of snow properties and of ice thickness to be made along the route of Exercise Musk-ox in 1946, and for weekly readings to be taken in 1947 at a dozen meteorological stations scattered across Canada (see Fig. 2). Measurements which were made every few inches throughout the snow layer included compressibility, temperature, thickness, density, free-water content, and crystalline structure. The variations found in snow were very great. Density of drifted snow in the Arctic reaches 0.45 compared with 0.1 for fresh snow. The original device for measuring compressibility although it had a range of from 1 to 10,000 gms/cm^2 has had to be extended at both ends [KLEIN, 1945]. With the object of furthering research and coordinating scattered effort, the National Research Council of Canada called a "Conference on Snow and Ice Research" in September 1947, which was attended by 70 scientists

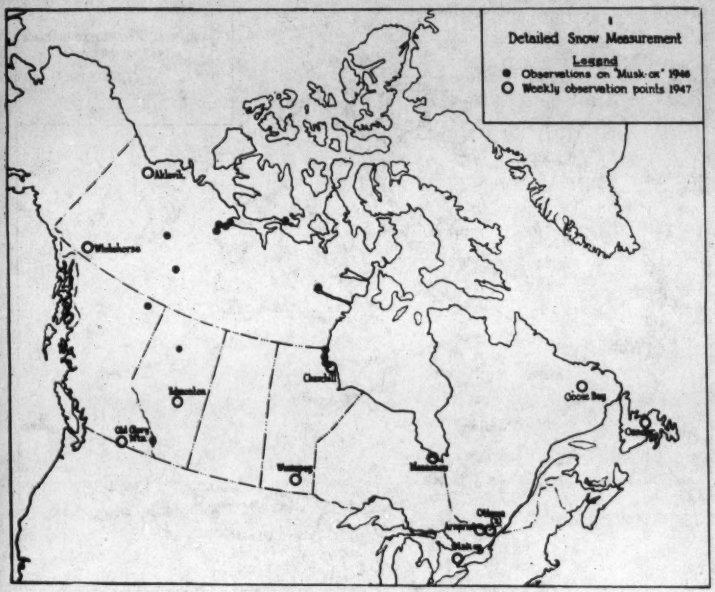

Fig. 2--Stations at which physical properties of the snow cover have been systematically measured in Canada

and engineers active in that work. A permanent committee under the chairmanship of P. D. Baird, Director, Montreal Office of the Arctic Institute of North America, was established to ensure continued effort and international cooperation [Hydrology: NATIONAL RESEARCH COUNCIL, 1947].

Oceanography--Prior to the War, oceanographic work in Canada was almost entirely limited to charting of coastal waters by Dominion Hydrographic Survey [Oceanography: HYDROGRAPHIC AND MAP SERVICE, 1946] and to biological investigations at six fisheries research stations. Recently regular studies of the temperature, salinity, and currents in the Gulf of St. Lawrence and off the Atlantic coast have been started and interest in physical oceanography is increasing [Oceanography: all other references].

Seismology--Under E. A. Hodgson the normal work of the Seismological Division of the Dominion Observatory of maintaining six seismic observatories (see Fig. 3), and publishing the bibliography of seismology [Seismology: E. A. HODGSON, 1929-1947, 1945b, 1945c, and 1946] has continued. In addition, with the help of mining companies rockbursts have been extensively studied for eight years past [Seismology: E. A. HODGSON, 1938-1945 and 1945a; ROBSON, 1946], while a new study of crustal structure was started during the summer of 1947 by setting up three portable seismograph stations to record rockbursts occurring at Kirkland Lake. These have been occasionally recorded at Boston, 500 miles away and with increasing frequency at observatories nearer to the source, particularly Ottawa and Shawinigan Falls [Seismology: J. H. HODGSON, 1947a]. A single component Sprengnether seismograph was installed at Kirkland Lake, while two, three-component instruments are being moved farther out from Kirkland Lake after each successive burst, until a travel time curve, based solely upon initial impulses, and thus independent of phase interpretations, has been established for the profile Kirkland Lake, Mattawa, Ottawa, and Boston (see Fig. 4). The foci of bursts can be established within about 100 feet in mine workings and high speed records on the instruments will be marked at one second intervals so that particularly accurate results should be obtained.

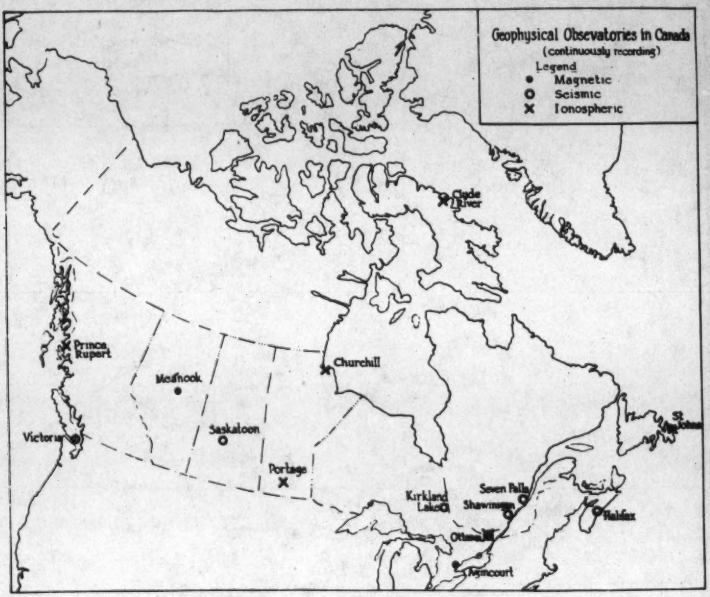

Fig. 3--Permanent geophysical observatories in Canada

Much seismic prospecting for oil has been carried out for many years in western Canada while smaller projects have been executed in Ontario and in the Maritime Provinces. The discovery in 1947 of an important oil field at Leduc, Alberta, has stimulated work so that about 17 seismic parties were operating before the end of that year. Altogether it is estimated that more than $15,000,000 has been spent in geophysical prospecting for oil in Canada, most of it by seismic reflection methods in Alberta [Seismology: J. H. HODGSON, 1947b; HOPKINS, 1947; MEDSGER, 1946; NATIONAL RESEARCH COUNCIL, 1947].

Terrestrial Magnetism--The North Magnetic Pole has been variously fixed in five widely different places (see Fig. 5) but it should shortly be located or its movements understood with much greater accuracy. Observers from the Dominion Observatory determined the elements of the Earth's field at 17 far northern points on Exercise Musk-ox and at 14 more points during the voyage of S. S. Nascopie in the summer of 1946. Parties transported by air and other means made observations in the summer of 1947, and a party based at Baker Lake in the winter of 1947-1948 should make many further readings to fix it accurately and improve the magnetic charts of northern Canada. A report on the location of the north magnetic pole is in preparation by R. G. MADILL [Terrestrial Magnetism: in preparation].

Due to the kind cooperation of the United States Government in supplying vital parts, the Department of Mines and Resources operated airborne magnetometers in mining districts of Canada in the summer of 1947. Private companies operated others over tens of thousands of square miles, thereby introducing an important technique for prospecting. For ground surveys, the Department is compiling detailed anomaly maps of several mining areas by providing control and collecting data from mining companies. These will by published shortly. Several base metal ore bodies have been found in Canada recently by the use of magnetometers [Terrestrial Magnetism; AMBROSE, 1945; GILCHRIST, 1945; KOULOMZINE, 1946; LUNDBERG, 1947; MASSÉ and KOULOMZINE, in preparation]. Not only are there several geophysical prospecting companies in Canada, but an increasing number of the larger oil and mining firms are employing permanent staff geophysicists.

Fig. 4--Sketch map to illustrate study of Ontario rockbursts

At several universities, research is being undertaken to improve the application and interpretation of electric and magnetic methods of prospecting [Terrestrial Magnetism: GILCHRIST, 1945; MASSÉ and KOULOMZINE, in preparation; RUEDY, 1945]. Work at two permanent magnetic observatories has continued throughout the War (see Fig. 3).

Atmospheric ionization--In this field various Canadian Government Departments, cooperating with the Canadian Radio Wave Propagation Committee in Ottawa and the Central Radio Propagation Laboratory in Washington, maintain six fixed and one mobile ionosphere observatories whose locations are shown in Figure 3. An extensive study of meteorological effects on radar propagation over land has been carried out on the prairies [Atmospheric Ionization: MILLER, DOHERTY, HALBERT, and SWANSON, 1945]. Ionospheric work is coordinated by F. T. Davies of the Canadian Radio Propagation Laboratory, Defence Research, Ottawa under whose direction a series of reports on ionospheric subjects have been issued [Atmospheric Ionization: all other entries]. Work on the allied fields of auroral intensity, auroral spectra, meteoric ionization, atmospheric ozone, cosmic rays, upper atmosphere electron temperatures, external radio noise, and charges on raindrops and snow crystals has been started since the War at Dominion Observatory and at Universities of Alberta, Montreal, Saskatchewan, and Toronto, but reports have not yet been published.

Radioactivity--Careful studies of pleochroic haloes by G. P. Henderson at Dalhousie University, Halifax, before the War showed that independent haloes caused by radium, and several other elements occurred in association with those long recognized as being caused by the whole uranium or thorium series. From the way these elements must have transported information is being derived about hydrothermal solutions, their rates of travel, chemistry, and the sizes of channels through which they passed. Henderson has recently resumed work and would be glad to obtain further halo-bearing specimens of biotite [Radioactivity: HENDERSON and SPARKS, 1939].

At the University of Toronto, radioactivity work is being resumed after a temporary pause caused by the departure of N. B. Keevil. Studies upon the average radioactivity, heat generation, and age of suites of Canadian rocks are in progress [Radioactivity: all other entries].

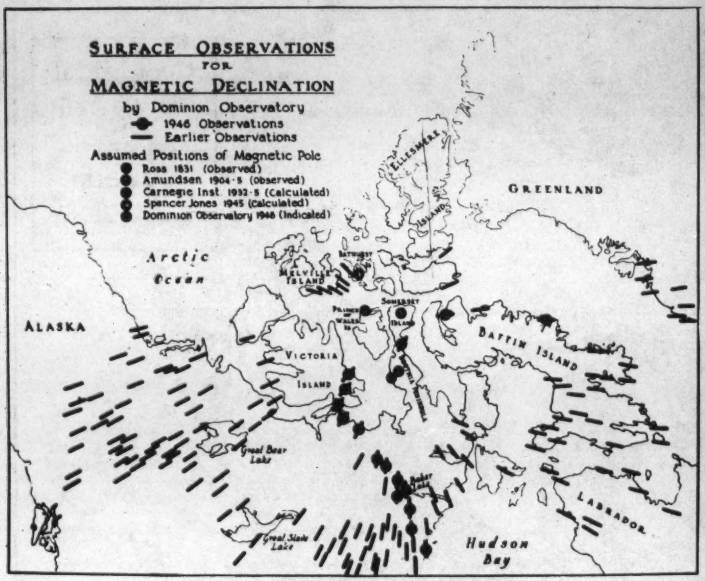

Fig. 5--Ground observations for magnetic declination made by the Dominion Observatory up to the end of 1946

Geothermometry--Temperatures and ventilation conditions have been subject to much careful study in Canadian mines with the object of improving working conditions underground [Geothermometry: BISCHOFF, 1947; CLELAND, 1933]. In 1947 Ontario Research Commission enabled A. D. Misener to start accurate measurements of temperatures, thermal conductivities, and specific heats of the rocks in several mines with the object of obtaining a better understanding of the sources of heat and its variations [Geothermometry: LANE, 1946; MISENER, in preparation].

Volcanology--This subject merges with more general problems in geology in countries where there are no active volcanoes. Hence in Canada no organization is specifically engaged upon studying it, but the references mention the latest papers on this and some allied subjects [Volcanology: all references].

Tectonics--One aspect of this subject is treated in Part II of this paper but it is worth mentioning that there has been a great change in the thinking of Canadian geologists with regard to tectonics within recent years. Although geologists concerned with the Maritimes and western Canada had long been aware of the importance of structural geology, those working in the Canadian Shield were primarily interested in petrology until sufficient work had been done in mines to show that many faults and folds could be deciphered in pre-Cambrian rocks. An important symposium of structure at 100 Canadian mines and camps is now being prepared [Tectonics: M. E. WILSON, in press] while other references [Tectonics: all other entries] indicate the present activity in this subject.

. So brief a summary of scattered work cannot hope to be complete, but it is hoped that most of the more important activities of Canadian geophysicists have been mentioned. To acquaint them and others with the progress in these many lines of endeavour the Associate Committee on Geodesy and Geophysics has arranged to issue to those who ask for it a quarterly annotated bibliography of Canadian papers with notes on current field work and research [General: CANADIAN GEOPHYSICAL BULLETIN, 1947].

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PRECISE LEVELLING ON THE ALASKA HIGHWAY

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Abstract--This paper presents the history of precise vertical control in Alaska and the Yukon; discusses particular problems encountered in bench-mark construction and description when working in the northern latitudes; and comments on the evidence indicating regional Earth movement.

Even before the Second World War, the eyes of the world were being focussed on the Arctic regions. With the advent of war and the impetus of improved aviation, each country bordering on the Arctic realized the imperative need of exploring and mapping the unknown spaces in this vast area. To the surveyor and mapmaker, the modern method of mapping remote areas is by aerial photography with horizontal control furnished by astronomical fixes and distances measured by electronic devices. Unfortunately there are no short-cuts for obtaining vertical control; elevations of even a low order of precision still have to be obtained by the slow monotonous procedure of spirit levelling. Although the radar altimeter is a step in the right direction and a valuable aid to aerial navigation, it is far from being a precise surveying instrument. Hence vertical control in remote regions requires running lines of levels from points of known elevation, and the purpose of this paper is to outline briefly the growth of the existing precise vertical control in Alaska and the Yukon.

The earliest line of precise, or first-order levelling, in the North American continent north of latitude 60°, was started in 1908 by the Geodetic Survey of Canada in connection with the demarcation of the 141st meridian which defined the Alaska-Canada Boundary northward from Mount St. Elias. The first precise level bench mark, P-42R, on this line was located at White Pass, British Columbia, where the White Pass and Yukon Railway cross the Alaska-British Columbia Boundary. This bench mark was a four-inch disk cemented in the top of a ledge of bed rock at track level and now 39 years later is apparently in as good condition as the day it was placed. From this bench mark a line of precise levels was carried northward over the railway, some 91 miles to Whitehorse, Yukon Territory. From Whitehorse the levels were run over the historic Dawson Trail crossing the Yukon River at Yukon Crossing and again at Dawson City and continuing on the south side of Yukon River until in the fall of 1911 the 141st meridian was reached at Boundary Monument No. G in latitude 64°05'. The field work was done by D. H. Nelles of the Canadian Boundary Commission and approximately 500 miles of precise levels were run in 1908, 1909, and 1910. The route beyond Whitehorse was little better than a poor wagon trail and it was a remarkable achievement to carry this work to completion in three short summer seasons. Permanent bench marks were established every ten miles and they were either disks in bed rock or in four-inch iron pipes, 58 inches long, with a spread base and a brass cap on top which projected about six inches above ground. Three-year tidal observations at Skagway during 1908, 1909, and 1910 determined the elevation of Tidal B. M. No. 3 to be 19.57 feet above mean sea-level. O. M. Leland of the United States Coast and Geodetic Survey, in 1910, ran first-order levels over the White Pass and Yukon Railway from Tidal No. 3 at Skagway to P-42-R at White Pass, a distance of only 20 miles but a climb of 3000 feet from sea-level. It was therefore possible to place the Yukon levels on mean sea-level datum when the 141st meridian was reached in the fall of 1911. It should be noted that, while it was based on mean sea-level datum, the line was in the nature of a spur as there was no circuit closure to test its accuracy.

The next levelling north of the 60th parallel of latitude was carried out in Alaska and is described in Special Publication No. 169 of the United States Coast and Geodetic Survey. Some 890 miles of first-order levelling were run in 1922 and 1923 by F. W. Hough and H. Odessey. The levels started at Seward and ran northward over the Alaska Railroad to Fairbanks in latitude 64°55' and then southward over the Richardson Highway to Valdez. At both Seward and Valdez tidal observations, covering a four-year period, determined mean sea-level datum and thus a circuit was formed by the loop of 890 miles of levels. The closure was very small and well within the probable error of a mean sea-level determination at an Alaskan seaport. The bench marks established on this work were placed at intervals averaging around three miles and were generally the standard disks placed in the top of concrete piers, "which were heavier and set deeper in the ground because of the severe Alaskan winters than is the usual practice."

It was not for another 20 years that the next precise levelling was carried out in this area. In 1942 the Alaska Highway was started as a war measure and was primarily to form a service road to airfields on the Northwest Staging Route joining Edmonton, Alberta to Fairbanks, Alaska. In 1943 the United States Coast and Geodetic Survey received instructions to carry out triangulation and first-order levelling along the Alaska Highway from Whitehorse, westward to Big Delta, Alaska. The levelling was started late in June at Whithorse and was completed by the middle of October. Three levelling parties under Taylor, Cowlie, and Tilghman ran in all 585 miles of levels from the original bench mark P-42-R at White Pass, British Columbia to Big Delta, Alaska, where a connection was made to bench mark W-6 which had been established in 1923 on the Richardson Highway. The completion of this line in the short period of four and a half months was an amazing performance which was only made possible by excellent organization backed up by the resources of the United States Army. The levelling operations were seriously handicapped throughout by the fact that the permanent Alaska Highway was then in the process of being constructed. The Army Pioneer road was built in 1942 and formally opened in November of that year, but the actual highway roadbed was not constructed until 1943 and indeed certain large bridges were not built until 1944. The levelling had to be done in sections and it was a race against time and the freeze-up, but on October 14 the gap between the eastern and western sections was closed at a point about nine miles west of White River. For reasons explained later the levelling started at White Pass instead of at Whitehorse as was originally intended.

As is now the practice of the United States Coast and Geodetic Survey, permanent bench marks were placed at intervals of one mile. When bed rock or large boulders were not available in which to cement the disks, the standard concrete piers were erected. These piers were made exceptionally long, varying from four to six feet, and were sunk from 12 to 18 inches in the frozen ground if frost was encountered. A special type of bench mark was used in areas where permanently frozen ground was encountered. This was a five-foot section of three-inch iron pipe with a four-inch bell at each end. The pipe was filled with concrete and the disk was set at the top end and the lower end was pre-cast in a cement carton about 18 inches long and 12 inches in diameter. The pre-cast bench marks were set in the frozen ground so that the top would project about one foot above ground.

The Alaska Highway starts in Canada at Dawson Creek, British Columbia, which is 500 miles by rail on the Northern Alberta Railway from Edmonton, Alberta. As stated before, the Highway was built to service the airports. The main airports are at Fort St. John, Fort Nelson, Watson Lake, and Whitehorse, which are, respectively, 50, 300, 634, and 917 miles from Dawson Creek. The Alaska-Yukon Boundary is 1221 miles by the Highway from Dawson Creek. In 1944 the Geodetic Service of Canada was instructed to extend its precise level system to Whitehorse. The nearest junction point of the Canadian level net was at Edmonton and as levels in 1916 had already been run some 160 miles towards Dawson Creek, it meant that roughly 1250 miles of precise levels would be required. The operation was carried out during the years 1944, 1945, and 1946, and because it was a strictly civilian project being executed in wartime when both manpower, especially technicians, and mechanical transport were short, the work entailed considerable difficulties. The average field season was limited to three and a half months. Two parties were employed in 1944, one under G. S. Raley, extending the levels over the Northern Alberta Railway to Dawson Creek, and the second under D. McMillan, starting operations at Dawson Creek and ending at mileage 235 on the Alaska Highway. In 1945 two parties were again put in the field. One party under L. O. R. Dozois started at Whitehorse from U. S. bench mark No. E-1 and worked eastward reaching mileage 674. The second party under D. J. Fraser continued the levels westward from mileage 235 across the Rockies and ended at Muncho Lake at mileage 454. In 1946 one party under G. S. Raley, working, eastward, closed the gap between Edmonton and Whitehorse when Muncho Lake was reached.

On the Candian section, the usual practice of the Geodetic Service of Canada was followed in placing permanent bench marks at intervals averaging two and one half miles. The standard iron pipe bench mark was utilized throughout. This is a 2 1/2-inch iron pipe, five feet long with a seven-inch foot plate and brass cap on top. In position the cap projects six inches above ground and a stone cairn is built in its immediate vicinity both as a means of identifying the bench mark and also to protect it. Every 20 miles, if a concrete supporting structure or bed rock was not available for a bench mark, a standard concrete pier extending six feet below the surface and projecting one foot above ground with a square top of 12 inches was built. It might be stated that permanent ground frost within six feet of the surface was not encountered on the section of the Highway east of Whitehorse.

Many factors are important in the development of a national vertical control system, but none take precedence over the establishment of a permanent ground record. Permanency, stability, accessibility, and recoverability are features which are desirable to secure when selecting the site and the type of bench mark best suited to the country where it is used.

The Alaska Highway was peculiar in that there was a minimum of artificial structures such as permanent buildings and in certain sections a singular lack of topographical features such as rivers and lakes. Great care had to be used in selecting the sites for bench marks which should be readily accessible from the highway and yet far enough away to avoid destruction by road maintenance. The site should not be in low ground with heavy loam or muck but preferably should be located in sand or gravelly soil with a good natural drainage. A stone cairn erected immediately behind the bench mark has been found by experience to have long life and to be a ready means of identification and protection.

In Canada it is a practice, before each revision of a precise levelling publication, to carry out a field inspection for the purpose of rewriting bench mark descriptions and to remove from the records any which have been lost or damaged. These inspections usually take place 15 or 20 years after the levels have been run and for an inspection to take place only two years after a line of levels has been run was most unusual, but this was done in the case of the 1943 U. S. levels in Canada. Owing to the fact that these levels were run when the actual construction of highway was under way, it was realized that the descriptions would of necessity be inadequate. A casual inspection in 1944 of a number of these bench marks revealed that because of the great changes which had taken place in one year, it was imperative that new descriptions of the bench marks should be written as soon as possible if the ground record was to be preserved. It was decided that the United States survey would carry out this inspection in Alaska and the Canadian survey would attend to the inspection in the Yukon. The inspection in Canada was carried out in 1945 and the results are given in two sections. On the railway section between White Pass and Whitehorse, 116 bench marks were established in 1943. In 1945 it was found that 37 per cent of the bench marks were in bed rock, 31 per cent in concrete piers, 17 per cent in boulders, three per cent in iron pipes, and the loss was ten per cent. Along the highway section between Whitehorse and the Alaskan Boundary, of the 320 bench marks established in 1943, 70 per cent were in piers, seven per cent in boulders, four per cent in bed rock, three per cent in iron pipes, and 15 per cent nad been lost. It is interesting to note in comparison that the routine inspection of bench marks in Canada reveals a loss of 13 per cent takes place between 10 or 15 years after their establishment. The causes of this excessive loss in two years were stated as deviations from the Army Pioneer road over which the line of levels was run; minor relocations on the Highway; destruction by heavy road machinery used by maintenance crews and by telephone right-of-way crews; and finally heaving by frost action.

On the section of the Highway between White River, mile 1169, and Beaver River, mile 1200, permanent ground frost was encountered in 1943. On this section the pre-cast iron-pipe bench mark described earlier in this article, was used by the American survey. Permanent ground frost is a condition which occurs in polar regions where the summer heat is not sufficient to thaw the ground more than a foot or two below the surface. The only experience the Geodetic Service has had with this condition was encountered on the Hudson Bay Railway to Churchill, Manitoba. The northerly 150 miles of this line ran through tundra country where permanent ground frost from a few inches below the moss covering extended to a depth varying from 20 to 100 feet, and where in the middle of summer the gound is never thawed out more than one or two feet below the surface. The problem of erecting permanent bench marks in areas of perpetual ground frost was apparently unique in the annals of national level systems. In 1938 when this Service was confronted with this problem, it could not benefit from the experience of other national surveys as to the proper method to be followed. The procedure finally developed by this Service was to select a site sufficiently distant from the railway so that it would be unaffected by the drainage contiguous to it. The top insulation, mostly moss, was then carefully removed and a hole in the frozen ground five feet deep and five feet in diameter was blasted out. A concrete base ten inches thick covered the bottom of the hole and on it was built a concrete pier sixteen inches square at the bottom and 12 inches square on top. The pier and base were built as a monolith and were reinforced with iron rods. The disk was set in the top of the pier which was at ground level. The hole was back-filled and left until such time as it was again frozen before its elevation was ascertained. The original covering was replaced and three feet of dry moss was added for extra insulation. A wooden tripod was erected on the site and a concrete plaque marked B. M. was hung on it. It is felt that a monument of this nature will hold its elevation as long as the area remains in the category of permanently frozen ground. The importance of preserving the original insulation and adding to it was derived from the experience gained during the construction of the Hudson Bay Railway in this area.

Before leaving the question of bench marks in permanently frozen ground, it is instructive to quote from the report of the inspection of 1945, speaking of the pre-cast iron pipe bench mark placed by the United States Coast and Geodetic Survey in the area lying west of White River. "The impression was gained that this type of bench mark will not hold its elevation. The fault does not

lie in the design of the mark but in the nature of the site where it was planted. No doubt in the fall of 1943 the ground gave every indication of being permanently frozen but in August 1945 there was no sign of frost within six or eight feet of the surface. It is probable that the construction of the highway, by removing the insulation from the surface and by lowering the level of the ground water, had thawed all land within 50 to 100 yards on each side of the highway. Apparently low ground, usually muskeg, was selected for the sites on the assumption that the frozen ground in these muskegs would be more permanent but with the thawing of the ground such sites were the worst possible."

Yukon and Alaska has long been recognized as a center of seismic activity. The Dominion Seismologist reports no less than 14 major earthquakes in this area in the period 1912 to 1944. It is logical to deduce that the prevalence of earthquakes is an indication of the lack of isostatic equilibrium. In an area of known seismic activity it may be expected that relevelling of a precise level line would reveal the existence of a tilt in the Earth's crust if of appreciable magnitude. Earlier in this article mention was made of the intention of the United States Coast and Geodetic Survey to start their 1943 levels from the 1908 levels at Whitehorse. However in picking up the 1908 levels it became evident that a systematic discrepancy existed between the two levellings which could only be accounted for by a tilt of the Earth's crust. On this account the 1908 levels were retraced from Whitehorse along the White Pass and Yukon Railway to the original bench mark No. P-42-R at White Pass before a proper check could be obtained. The 1908 levels were checked as far north as the Takhini River, a distance of 115 miles from White Pass, and the divergence in this distance amounted to 4.924 feet; the latter levelling making the northern point lower in elevation than the 1908 levelling. Using the 1908 value for B. M. P-42-R and the difference of elevation, orthometrically corrected, obtained from the 1943 levelling, the elevation of B. M. W-6 at Big Delta was found to be 1.64 feet below the adjusted elevation of this bench mark assigned from the 1923 levelling. The value of 19.57 feet above mean sea level used for B. M. Tidal 3 at Skagway in 1911 was based on tidal observations covering a three-year period from 1908 to 1911. As the result of a two-year period of tidal observations from 1944 to 1946, a new value of 21.71 feet above mean sea level was determined by correlating observations at Skagway with simultaneous records at Ketchikan where a 19-year period was available. In 1944 the United States Coast and Geodetic Survey relevelled the section between Skagway to White Pass and has plotted a graph showing the divergence between the 1908 levelling and the 1943 relevelling between Skagway and Takhini, a distance of 135 miles. Assuming no errors in levelling and divergence to be the result of a tilt in the Earth's crust, the divergence curve is uniform from Skagway to mileage 78 on the railway, amounting to a rate of 0.023 foot per mile, with a greater but still uniform slope amounting to 0.063 foot per mile to Takhini. This change in slope coincides with a change in direction of the route from a north-northeasterly to a north-northwesterly course. It is interesting to note that the new determination of mean sea level at Skagway reduces the closure at Big Delta to a negligible amount.

When the results of the three years levelling, 1944 to 1946, along the Alaska Highway by the Canadian Geodetic Service became available, it was found that resulting elevation of the junction bench mark E-1 at Whitehorse derived from the 1400 miles of levelling from Edmonton, differed by 2.9 feet from the value resulting from U. S. levelling of 1943 and was more nearly in accord with the value obtained from the 1908 levelling. It has been mutually agreed by the two Surveys to hold the adjusted elevations for the junction bench marks at Edmonton and Big Delta and to use the 1946 elevation for the Tidal B. M. No. 3 at Skagway, and to accept the weighed mean as the adjusted value for the junction B. M. E-1 at Whitehorse. The effect of this adjustment is a correction being applied at a rate of 0.0020 foot per mile on the leg from Edmonton, 0.0015 foot per mile from Skagway and 0.0005 foot per mile from Big Delta.

In the foregoing an attempt has been made to trace the development of precise vertical control in Alaska and the Yukon. The effect of seismic activity and permanent frozen ground on precise levelling has been briefly discussed. Incidentally it narrates a tale of teamwork between two national geodetic surveys and adds another link to the late President Roosevelt's "Policy of Good Neighbors."

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VERTICAL MOVEMENT IN THE LOS ANGELES REGION, 1906-1946

Ernest J. Parkin

Abstract--The purpose of this paper is to present a history of the Coast and Geodetic Survey first-order leveling in the Los Angeles region, a description of the consequent office adjustments, and a discussion of the major areas of vertical movement, either of subsidence or uplift, revealed by comparison of surveys of different years.

History of leveling and adjustments

During the last 40 years, the United States Coast and Geodetic Survey has developed a rather extensive level net in the Los Angeles region. Many of the lines of this net have been releveled either partly or completely at various times during the period to determine changes in the elevations of the bench marks. The area considered in this paper is shown in Figure 1.

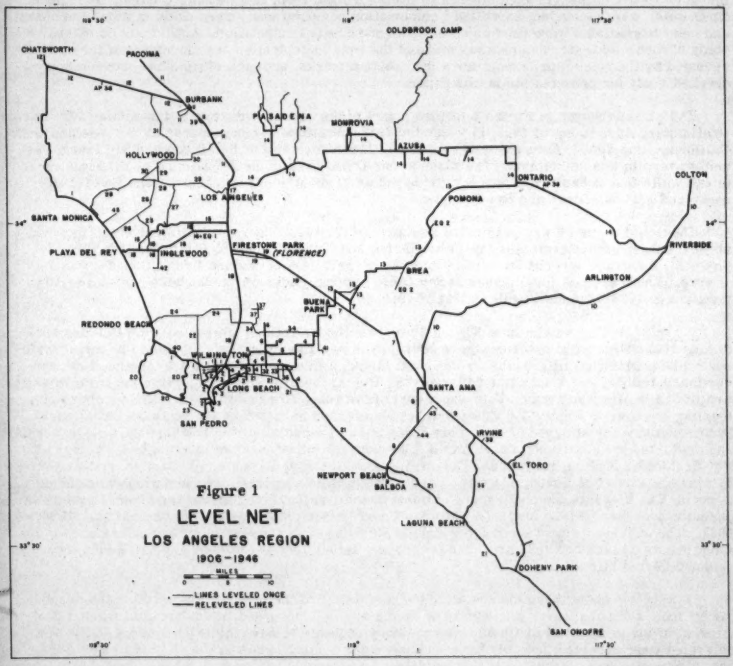


Figure 1
LEVEL NET
LOS ANGELES REGION
1906-1946

1906-1920--The first leveling by the United States Coast and Geodetic Survey in the area extended from San Onofre via Santa Ana to Colton, and was run in 1906 as a part of the line from San Diego to Barstow. This line formed a part of the link from San Diego to Goffs in the Adjustment of 1912. One of the stations at which mean sea level was held at zero in this Adjustment was located at San Diego. The value held was based on three years of gage records at the Quarantine Station (La Playa), 1906 to 1908. The first published elevations resulting from this leveling were based on the 1912 Adjustment and were included in Special Publication No. 18.

The next leveling in the area, from Chatsworth via Florence to Santa Ana, with a spur line from Florence to San Pedro, was a part of the line San Jose to Santa Ana which was run in 1920. Shortly after the completion of the 1912 Adjustment, a line of leveling from Brigham, Utah, via San Jose to San Francisco, California, had been finished. This line was adjusted to the 1912 value at Brigham and the mean sea level at San Francisco given by 16 years of tide observations from 1898 to 1913. The 1920 leveling was fitted to the resulting value at San Jose and the published elevations (1912 Adjustment) of marks at Santa Ana. These adjusted values were therefore in agreement with the 1912 Adjustment.

1923-1927--In 1923 the United States Coast and Geodetic Survey extended a line of first-order leveling from Los Angeles to Pomona. This line of leveling was run over the Pasadena Base which had been measured in connection with the triangulation for the base line used by Michelson in his determination of the velocity of light. This leveling marked the beginning of a period of about five years which saw the development of the network shown in Figure 1, as well as the releveling of the old work from Chatsworth via Florence to San Pedro and from Santa Ana to Ontario. For these lines which were releveled, so-called "combination computations" were made in which the old and new observations were used together to form a single computation. Apparently no extensive study of these separate runnings was made at the time to determine any movement of the marks revealed by the releveling, except for a few isolated marks, and lack of time has prevented any detailed study for presentation in this paper.

The circuits shown in Figure 1 formed a part of the network adjusted in the Southern California Preliminary Adjustment of 1928, in which the 1912 elevations of bench marks at San Jose and Goffs, California, and Yucca, Arizona were held fixed. Mean sea level at San Diego and San Pedro was held at zero in this adjustment. The plane at San Diego used in the Adjustment of 1912 was retained while that at San Pedro was a value based on 31 months of tide observations (1923-1926) compared with San Diego and San Francisco.

The net of Figure 2 was readjusted as a part of the 1929 General Adjustment which included all of the first-order leveling in the United States and Canada (some 65,000 miles). In this adjustment, mean sea level at 26 tide stations, 21 in the United States and five in Canada, was held at zero. The mean sea level planes at San Diego and San Pedro which had been held in the Adjustment of 1928 were used again in that of 1929.

1931-1932--The net shown in Figure 2 was practically entirely releveled from October 1931 to May 1932 and several new lines were added. The new lines were an east-west line and a north-south line over Signal Hill, a line on Terminal Island, a line from Santa Ana to another tidal connection at Balboa, and a spur line to Pasadena. During the following winter, the line from Santa Ana to San Onofre was rerun. This was a part of the releveling to San Diego. The extent of this leveling is shown in Figure 3. This leveling was adjusted as a part of the Southern California Supplementary Adjustment of 1934. This Adjustment covered all of the southern part of California and held fixed the elevations, based on the 1929 General Adjustment, of junction bench marks at Needles, Cadiz, Colton, Saugus, and Goleta, California; and at Hassayampa, Salome, and a point 27 miles southeast of Yucca, Arizona. The following mean sea level determinations were held at zero: San Diego, based on 20 years of observations, 1906-1925; Balboa, based on 12 months of observations, June 1931 to May 1932; and San Pedro, based on nine years of observations, 1924-1932. The differences between these values at San Diego and San Pedro and the values used in the Adjustments of 1928 and 1929 are: San Diego, new datum 0.03 foot higher; and San Pedro, new datum 0.03 foot higher.

1933-1934--About three months after the completion of the leveling discussed in the preceding paragraphs, the Long Beach Earthquake of March 10, 1933 occurred, which aroused a great deal of interest in the problem of Earth movement. Many requests to have the level network in the area releveled were received, not only from engineers and seismologists in the vicinity of Los Angeles, but also from others interested in the problem. An extensive program of releveling and new leveling which began in September 1933 and ended in April 1934 was then undertaken. The extent of this work is shown in Figure 4. This net was adjusted by holding fixed, the same tidal planes at

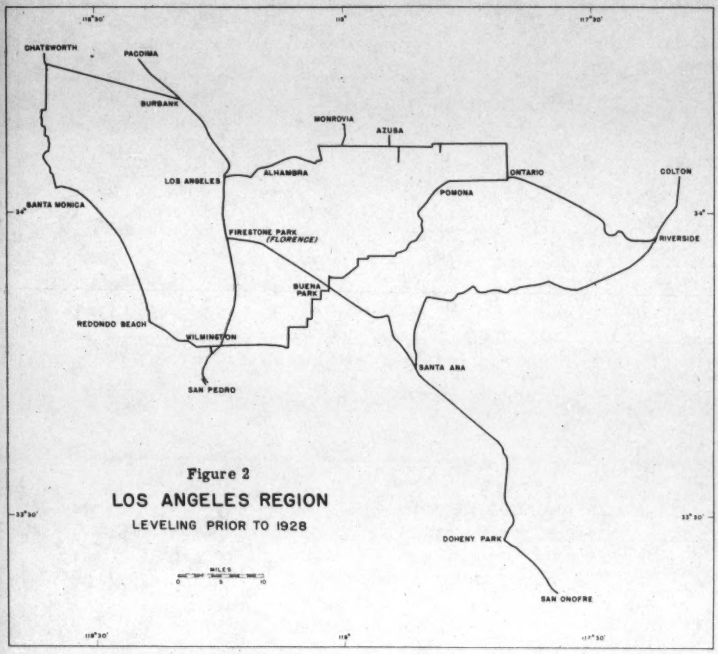


Figure 2

LOS ANGELES REGION

LEVELING PRIOR TO 1928

San Pedro and Balboa and the elevations, based on the Adjustment of 1934, of junction bench marks at Girard, Los Angeles, Colton, and Arlington.

The circuit closures indicated that the leveling had not been extended far enough to the southeast to reach undisturbed bench marks. For that reason, no elevation was held fixed at Doheny Park. It was not until April 1944 that leveling was extended from this point to stable bench marks near San Onofre. To fit this later leveling it was necessary to readjust the lines from Doheny Park north to Santa Ana and northwest to Newport Beach, holding an elevation at San Onofre based on the Southern California Supplementary Adjustment of 1934.

1935-1939--The next leveling in the area under consideration consisted of two of the eight cross lines, which were leveled in 1935 to establish a basis for the study of movements of bench marks near fault lines in Southern California. One of these two lines is in the vicinity of Inglewood and the other is near Brea. Late in 1935 a line of leveling, about 3 1/2 miles in length, was run along the shore line near Huntington Beach. This line was run for the purpose of marking the mean high-water line at the request of the California State Senate Oil Investigating Committee, the expenses being borne by the State. These lines were fitted to the results of the adjustment of the 1933-1934 leveling.

Two lines of leveling in the region were run in 1939, single-run releveling from Burbank to Saugus and second-order leveling from Irvine to Laguna Beach.

1941--In the summer of 1941 a small portion of the net in the vicinity of Long Beach was releveled for the purpose of determining reported Earth movement in the vicinity. The extent of this work is shown in Figure 5. The adjustment of this leveling was accomplished by holding fixed

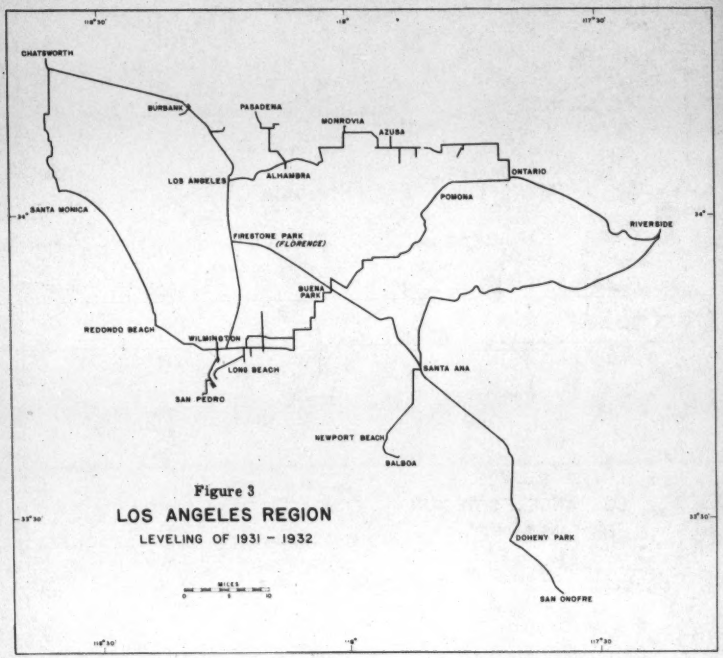


Figure 3

LOS ANGELES REGION

LEVELING OF 1931 - 1932

the elevations of junction bench marks based on the adjustment of the 1933-1934 work. These bench marks are located at El Segundo, Florence, and in eastern Long Beach. The 1924-1932 tidal plane at San Pedro was again held at zero.

1944-1946--A statement concerning the releveling of 1944 from Doheny Park to San Onofre has already been made in discussing the adjustment of the 1933-1934 work. In January and February of 1945, ten spur lines to airports in this region were run as a part of a war-time program of determining elevations at airports.

During the War, considerable concern was aroused by the subsidence of certain bench marks at the eastern end of Terminal Island. Officials of the United States Navy were very much interested because of the construction of a large graving dock at the Fleet Operating Base. Others interested were the engineers of the Southern California Edison Company, which has a large plant on the island, and officials of the Long Beach Harbor Department.

After considerable study, the United States Coast and Geodetic Survey releveled much of the net and ran a large amount of new leveling. The extent of this leveling, with the addition of the Doheny Park-San Onofre line and the airport lines, is shown in Figure 6.

In July 1945, at the beginning of the work, a line was run on Terminal Island. At the request of the Navy, this line was releveled in May 1946 near the conclusion of the project. The releveling started from the tidal bench marks at San Pedro, spanned the channel to Reservation Point at the southwest extension of the island, and then extended back along the route of the earlier work to the northeast corner of the island. However, the line was not extended far enough eastward to reach undisturbed marks and, as a result, has to be treated as a spur line.

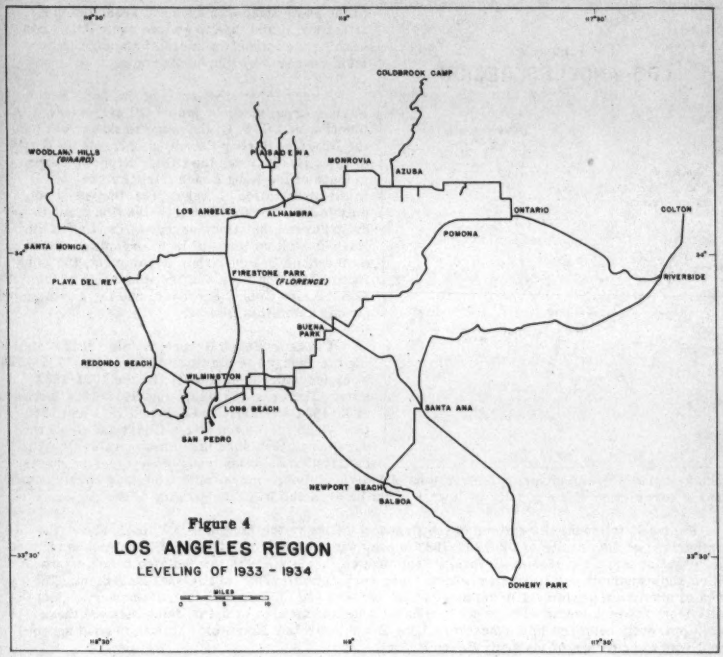


Figure 4

LOS ANGELES REGION

LEVELING OF 1933 - 1934

The leveling of 1945-1946, together with the 1944 line from Doheny Park to San Onofre, was adjusted by holding fixed the 1924-1932 mean sea level at San Pedro and the elevations of junction bench marks, based on the last previous adjustment, at Santa Monica, Van Nuys, Pacoima, Los Angeles, Alhambra, Brea, and Orange. The Terminal Island leveling of 1946 was simply treated as a spur from the initial mark.

The elevations resulting from these adjustments of the various levelings are being compiled in tabular form and will be issued by the United States Coast and Geodetic Survey as one of its official publications. Anyone interested in making a detailed study of the area will be furnished with a copy upon request when it becomes available.

In connection with this compilation, it was realized that the comparison of the elevation of a particular bench mark determined prior to 1928 and that determined later would be open to the criticism that the difference would be a combination not only of the movement of the mark itself and accidental errors of observation, but also of the difference in datum. In order to eliminate the difference in datum, a special adjustment of the leveling prior to 1928 was made to fit it to the Southern California Supplementary Adjustment of 1934, which is the common datum of the later elevations. This adjustment held fixed the elevations of bench marks at Chatsworth, Burbank, and Riverside and the later mean sea-level values at San Pedro and San Diego.

Comparison of results

It is the intent of this paper to discuss only the differences in elevation revealed by a comparison of the 1931-1932 survey with that of 1945-1946, that is, between the work done just prior

to the earthquake of March 10, 1933, and the latest work, and then to go into some detail concerning the important areas of regional movement revealed by this comparison.

A very exhaustive study of the Long Beach Harbor Area, made by James Gilluly, Harry Johnson, and U. S. Grant, was issued in 1946 by the Board of Harbor Commissioners of the City of Long Beach under the title, "Report on Subsidence of the Long Beach Harbor Area, 1945." In the preparation of that report, they used not only leveling by the United States Coast and Geodetic Survey, but also surveys of the United States Navy as well as those of local organizations, such as the Long Beach Harbor Department, the Long Beach City Engineer's office, the office of the Los Angeles County Surveyor, and the Los Angeles County Sanitation District.

The Long Beach Report contains charts showing the changes in elevation between the 1906-1928 work (considered as a unit) and the 1931-1932 survey; between 1931-1932 and 1933-1934; between 1933-1934 and 1941; and between 1941 and 1945 (for which the United States Coast and Geodetic Survey had furnished preliminary values). This report also contains many other types of charts, such as those showing changes in elevations of individual bench marks with time, and charts showing the correlation of the results with what might be expected from the geology of the region.

Figure 7, following the pattern of the first few charts in the Long Beach Report, shows the comparison of the results of the 1931-1932 survey with the leveling of 1945-1946 by means of lines representing equal changes in elevation. This sketch, neglecting the few isolated bench marks which show anomalous differences, shows three very definite areas of regional movement. The area of maximum settlement is centered at the eastern end of Terminal Island; another area of settlement appears centered at or west of Santa Ana; and an area of uplift, lying between these two, apparently centered in northeastern Long Beach near Los Alamitos. This is in good agreement with the findings of the Long Beach Report.

It will be noted from a study of Figure 7 that there is no basis for comparison in the area between eastern Long Beach and Santa Ana, nor east of Santa Ana, and for that reason we can determine the center of uplift and the center of subsidence near Santa Ana only approximately. Additional leveling in the area would be necessary to locate these centers more definitely.

The maximum value of uplift shown on Chart No. 2 of the Long Beach Report, which is a comparison of the work done just before and just after the earthquake of 1933, is 0.61 foot. The leveling of 1941 was not carried beyond this point where a proper check was obtained. It was therefore believed that no change had occurred between 1934 and 1941. The latest leveling, however, as indicated in Figure 7, shows that the amount of uplift has decreased to 0.38 foot, or, in other words, that the area has settled 0.23 foot since 1941.

Figure 8 is an enlarged view of the area of subsidence at Santa Ana. Sketch A in the figure is a comparison of the leveling run just prior to the earthquake (1931-1932) with that run just afterwards; B is a comparison of the 1931-1932, and 1945-1946 work. The maximum value of the settlement determined in 1933-1934, in about a year, is 0.40 foot. The maximum value shown in sketch B is 1.29 foot. The leveling of 1941 was not extended this far east so that no comparison is possible.

Figure 9 is an enlarged view of the area at Terminal Island and shows the startling progress of the subsidence in that vicinity during the period from 1931-1932 to the present time. Chart No. 2 of the Long Beach Report shows the changes in elevation over the same period as Figure 9-A, but covers a considerably larger area. Their chart reveals two small areas of subsidence, one located about 2 1/2 miles west and the other one mile east of the northeast corner of the island.

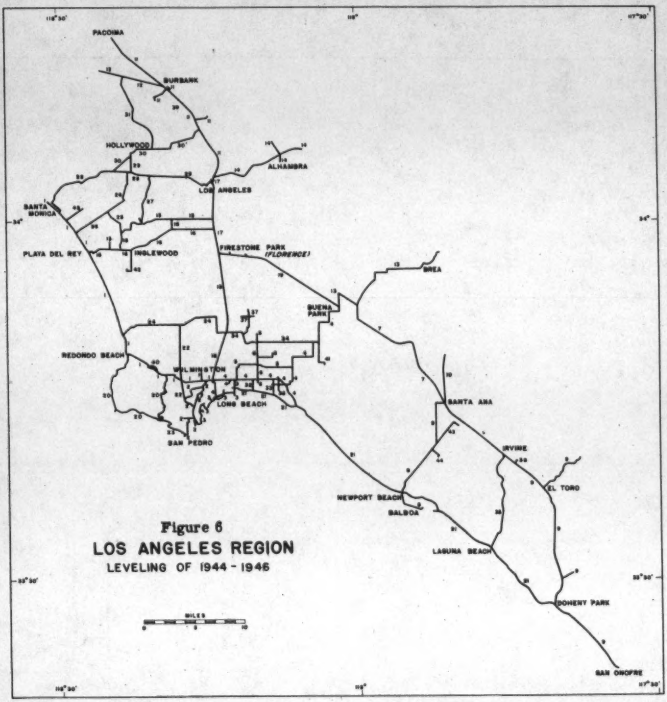


Figure 6
LOS ANGELES REGION
LEVELING OF 1944 - 1946

The western area has a maximum settlement of 0.25 foot and the eastern about 0.20 foot. In 1941 there was one center near the Southern California Edison Co. plant at the eastern end of the island with a maximum value of subsidence of 1.30 feet (see Fig. 8B). The leveling of July 1945 reveals continued subsidence which had increased to 4.24 feet (see Fig. 8C), and that run less than a year later, in May 1946, shows the subsidence still in progress, the value then having reached 4.95 feet (see Fig. 8D).

Figure 8E shows a comparison of the elevations determined in July 1945 and May 1946. The center of subsidence has deepened nearly three-quarters of a foot in about ten months. The importance of the problem is accentuated by the fact that the mark showing maximum settlement had an elevation of about 6.5 feet above mean sea level in December 1931 and had settled to an elevation of 1.5 foot in May 1946.

In view of the economic importance of the Los Angeles region, it is the opinion of the writer that a denser network of leveling should be developed and releveling undertaken periodically in order to obtain more definite information concerning the Earth movement taking place in the area.

Acknowledgement

The author expresses his appreciation to C. H. McLendon for his very valuable suggestions and assistance in the preparation of the sketches.

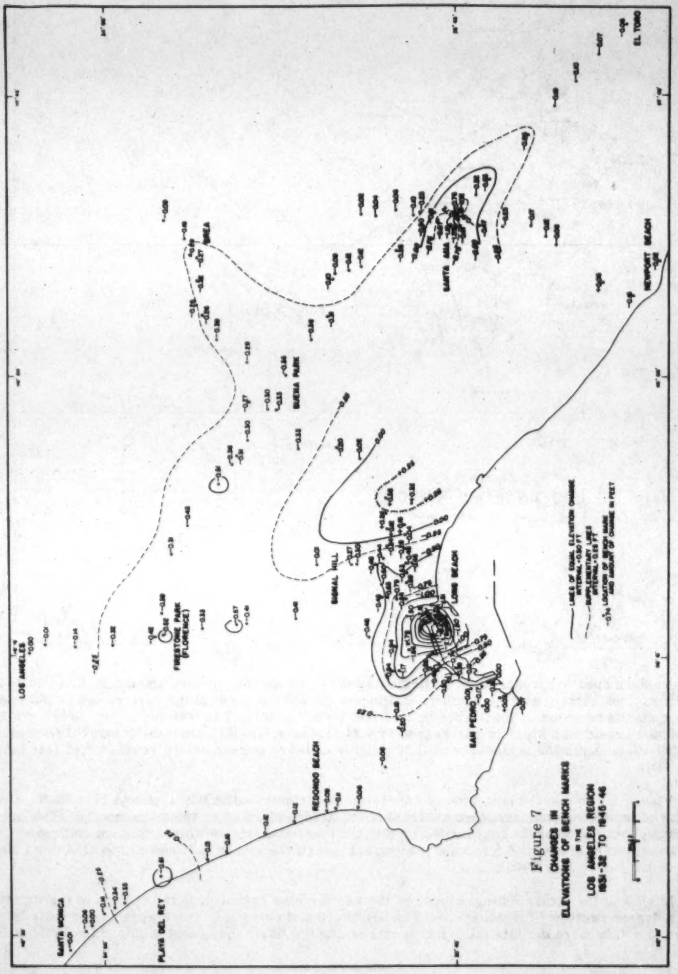


Figure 7
CHANGES IN
ELEVATIONS OF BENCH MARKS
IN THE
LOS ANGELES REGION
1931-32 TO 1945-46

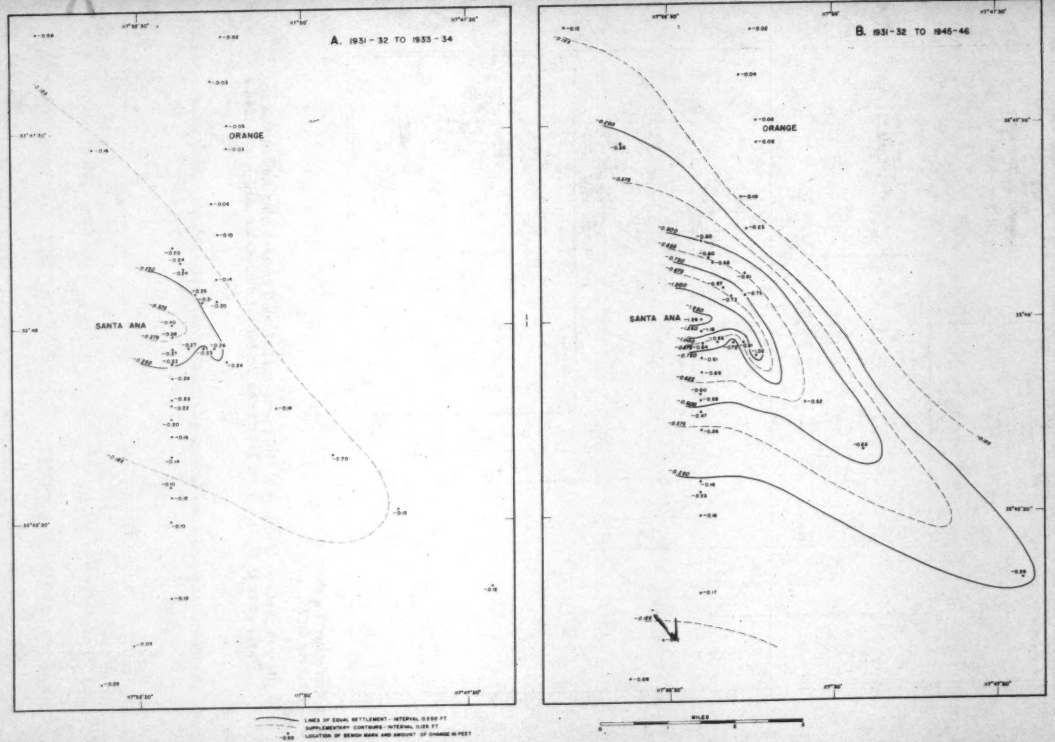
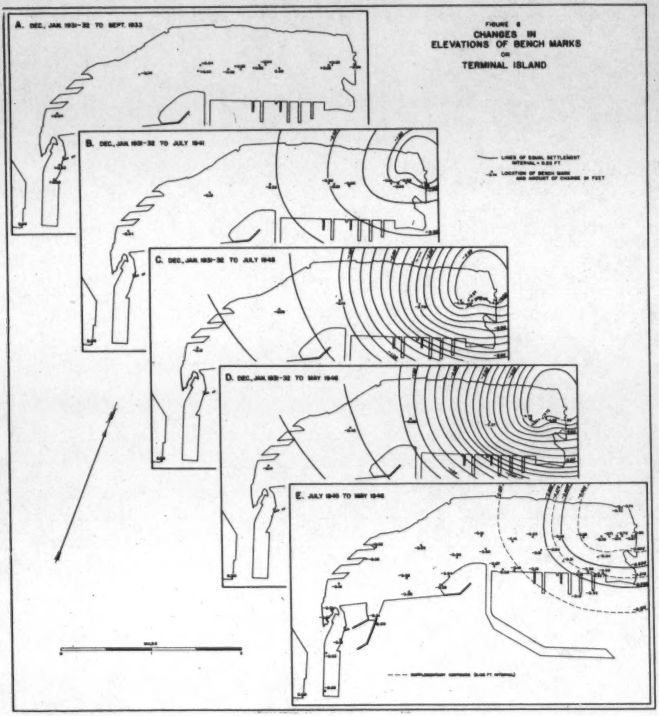

A. 1931 - 32 TO 1933 - 34
B. 1931 - 32 TO 1945 - 46
ORANGE
SANTA ANA
LINES OF EQUAL SETTLEMENT - INTERVAL 0.50 FT
SUPPLEMENTARY CONTOURS - INTERVAL 0.25 FT
LOCATION OF BENCH MARK AND AMOUNT OF CHANGE IN FEET
MILES

Fig. 8--Changes in elevations of bench marks at Santa Ana


A. DEC., JAN. 1931-32 TO SEPT. 1933
B. DEC., JAN. 1931-32 TO JULY 1941
C. DEC., JAN. 1931-32 TO JULY 1945
D. DEC., JAN. 1931-32 TO MAY 1946
E. JULY 1945 TO MAY 1946
FIGURE 8
CHANGES IN
ELEVATIONS OF BENCH MARKS
ON
TERMINAL ISLAND

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

(Manuscript received May 7, 1947; presented at the Twenty-Eighth Annual Meeting, Washington, D. C., April 30, 1947; open for formal discussion until July 1, 1948.)

Transactions, American Geophysical Union Volume 29, Number 1 February 1948

EARTHQUAKE INVESTIGATION IN THE VICINITY OF EL CENTRO, CALIFORNIA; HORIZONTAL MOVEMENT

B. K. Meade

Abstract--Following the earthquake in 1940 in the vicinity of El Centro, California, existing triangulation was reobserved to determine the magnitude and direction of shift of individual stations. A comparison of the results indicates that all stations east of the fault line shifted southeast and stations west of the fault shifted in the opposite direction. Maximum displacement between stations was about ten feet.

The United States Coast and Geodetic Survey has been engaged in the study of Earth movements by triangulation for many years. This is particularly true in California where tests have been made along several fault zones. The triangulation in the vicinity of El Centro, executed in 1935 and 1939, was not done for the particular purpose of studying Earth movements. However after the earthquake on May 18, 1940, this area proved to be an ideal location for such a study.

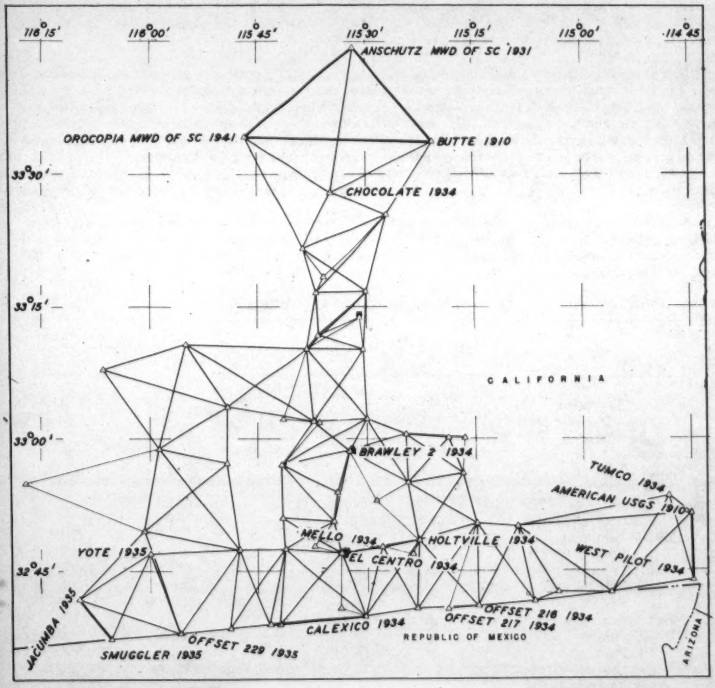


Fig. 1--First-order triangulation in the vicinity of El Centro, California

In 1941 reobservations were made over the triangulation network in this area. The extent of the new observations was about 40 miles east and west of the fault line and approximately the same distance north from the north end of the fault. A comparison of the new observations with the old indicates that the angular change at stations at a distance of 40 miles from the fault is due to unavoidable accidental errors rather than to actual Earth movement. The angular change at the extreme ends of this triangulation scheme (see Fig. 1) is given in Table 1.

Table 1--Angular changes at extreme ends of first-order triangulation scheme in the vicinity of El Centro, California

Station	Seconds of the angles		Difference
	1935-1939	1941	
	"	"	"
Tumco	29.16	29.16	0.00
American West Pilot	11.23	12.75	+ 1.52
	17.40	17.65	+ 0.25
Chocolate	43.89	43.27	- 0.62
Orocopia	12.24	11.19	- 1.05
Butte	04.53	05.45	+ 0.92
Yote	05.84	07.11	+ 1.27
Offset 229	09.49	09.79	+ 0.30
Smuggler	44.82	44.83	+ 0.01

Assuming that there is no Earth movement where the angular change is within the limits of accidental error, the heavy lines in Figure 1, fixed by previous adjustments, were used to control the adjustment of this network. Instead of adjusting the 1941 observations and comparing the results with the previously adjusted positions of the old work, it was decided to readjust the old observations, in order that the number and type of conditions in the two sets of observations would be identical. This adjustment was accomplished with one forward solution. Two eta columns were carried through the solution, one for the 1935-1939 work and one for the 1941 work. Then one back solution and one set of v's were computed for each of the two sets of observations. Statistics for the results of these observations are given in Table 2.

In Figure 2 the arrows indicate the changes in geographic positions of the triangulation stations near the fault line. These changes do not represent exact Earth movements, since the unavoidable errors of observation are combined with actual Earth movements. However if the statistics of these observations are examined, it is apparent that each set of observations is of excellent first-order accuracy and that the closures in all cases are approximately the same. Thus it must be concluded that the greater part of the indicated change was caused by actual Earth movement. The shifts in the vicinities of Holtville and Brawley are in close agreement with local inspection made shortly after the earthquake. From the two sets of adjusted values, maximum changes are as shown in Table 3.

All stations on the west side of the fault have shifted in a northwesterly direction and those on the east side have shifted to the southeast. In all tests of Earth movement in California the direction of shift has been identical, that is, stations west of the fault shift northwest and those to the east shift southeast.

Table 2--Data on results of observations

Item	Closures and corrections	
	1935-1939	1941
	"	"
Average triangle closure	0.92	0.85
Maximum triangle closure	2.70	2.34
Maximum correction to angle	2.73	1.86
Average V	0.35	0.33
Maximum V	1.74	1.29
Azimuth closures		
1 - American-West Pilot to Jacumba-Smuggler	1.70	4.47
2 - Butte-Anschutz to Jacumba-Smuggler	2.50	4.62
Closure before adjustment	One part in	
1 - Length	25,000	25,000
1 - Position	27,000	35,000
2 - Length	139,000	317,000
2 - Position	320,000	210,000
Closure after side and angle conditions were satisfied		
1 - Length	48,000	52,000
1 - Position	128,000	182,000
2 - Length	135,000	109,000
2 - Position	302,000	822,000

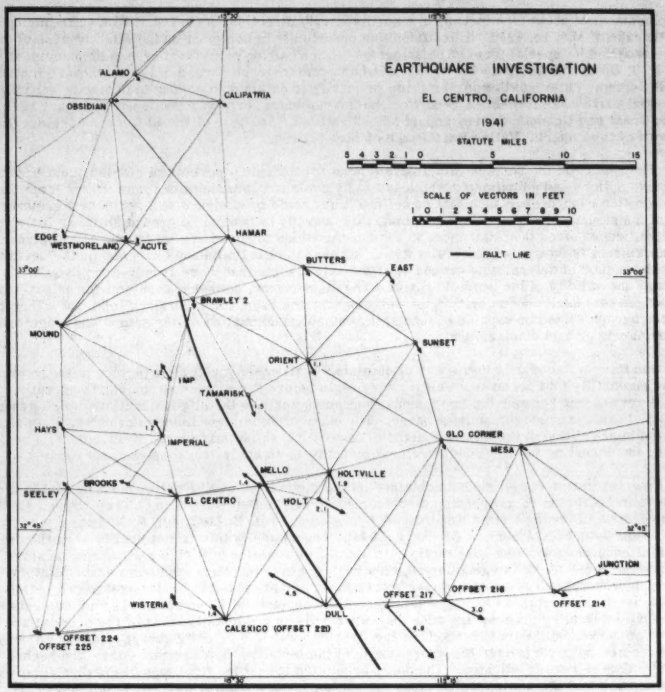


Fig. 2--Changes in geographic positions of the triangulation stations, El Centro, California

Table 3--Changes indicated by the observations

Item	Line	Change
Position	Offset 217	4.8 ft
Length	Offset 216-Dull	6.5 ft
Azimuth	Holtville-Mello	23.23 sec
Angle	At Dull from Calexico to Holtville	30.00 sec

The results obtained from this work are more conclusive than any previous test of this nature. This conclusion is based on two reasons: (1) The shirt in this area is better defined than that in previous work; (2) previous studies in other areas did not have sufficient observations to make identical adjustments. (In order to obtain the best results it is imperative that observations be repeated at the same stations and over the same lines.)

U. S. Coast and Geodetic Survey,
Washington 25, D. C

(Manuscript received May 7, 1947; presented at the Twenty-Eighth Annual Meeting, Washington, D. C., April 30, 1947; open for formal discussion until July 1, 1948.)

DISCUSSION

Frank Neumann (U. S. Coast and Geodetic Survey, Washington, D. C., September 11, 1947)--The geodetic surveys discussed in the paper by Meade indicate that a permanent horizontal

displacement of about nine inches, in a northwesterly direction, occurred at El Centro during the earthquake of May 18, 1940. This affords an opportunity to comment on the effectiveness of the accelerograph (a special form of seismograph) in measuring permanent ground displacement since the U. S. Coast and Geodetic Survey obtained an accelerograph record of the earthquake motion in El Centro. This installation was made primarily to obtain data needed in designing structures to resist earthquake forces. A report on the instrumental study was published in August 1941 in U. S. Coast and Geodetic Survey report MSS-9 entitled "Analysis of the El Centro Accelerograph Record of the Imperial Valley Earthquake of May 18, 1940."

The report on the seismogram analysis does not indicate a permanent displacement because the assumptions and adjustments which had to be made in computing the displacement from the acceleration record were such that no definite limit could be assigned to a permanent ground shift. From the structural engineering viewpoint, this inability to determine ground shift has little or no significance since the differences in the accelerations involved are infinitesimal. The engineer is fundamentally interested in acceleration. In this case the limitations imposed on the seismographic method of determining ground shift indicate clearly that there is no reason to question in any way the validity of the geodetic result. The discrepancy, however, does call for an explanation of the problems encountered in the seismogram analyses, for laboratory tests show that the accelerograph should be capable of furnishing valuable information on the nature and magnitude of permanent ground displacements.

One thing which stands in the way of obtaining in all cases a complete picture of the movement is the possibility that permanent shifting may begin before the accelerograph starts operating, but this is not serious because the instrument responds quickly to the slight vibrations which generally, but not always, precede the shifting phase. The other problem, now being eliminated, is an almost infinitesimal shifting of the accelerometer zero position which introduces, nevertheless, a serious hazard in converting the recorded acceleration curve to an equivalent displacement curve.

An acceleration curve, such as obtained on the instrument at El Centro, must be double integrated to obtain the corresponding displacement [see The Determination of True Ground Motion by Integration of Strong Motion Records: A Symposium by H. E. McComb, F. Neumann, A. C. Ruge, Bull. Seis. Soc. Amer., v. 33, no. 1, 1943]. Theoretically this is impossible when the differential equation governing such motions is applied to a motion of entirely unknown character because the constants of integration are, as a rule, not known. When applied to an oscillatory motion, however, such as an earthquake vibration, it is quite feasible to find axes which satisfy all reasonable doubts and these axes are tantamount to constants of integration. The adjustments in the double integrating process are such that any errors in the tentative axis of the original acceleration curve and the tentative axis of the first integral (the velocity curve) result in an error of simple parabolic form over the entire length of the tentative displacement curve (the second integral). This is readily adjusted. The only assumption is that the final axis of the displacement curve be such that the motion indicated is oscillatory about a central axis. It is not necessary that the acceleration record be available from the beginning of the motion.

A permanent displacement is indicated on the first integral (velocity) curve as a large wave at or near the beginning of the record, and it is of such nature that the area beneath the curve on one side of the axis is not compensated by an equal area beneath the curve on the opposite side. This signifies a displacement to one side of the axis which is not compensated and is therefore permanent. As acceleration records are 75 sec long and the permanent shifting should be over in less than five sec, a satisfactory axis for the velocity curve should be obtained from the last 70 sec of the curve if the first five sec or more seem erratic. Projecting such an axis through this early portion should give a reliable picture of the displacement whether it be permanent or not.

The effect of accelerometer pendulum instability, as experienced at El Centro, is to shift the axis of the acceleration curve, thus breaking the continuity of the computed velocity curve which is so essential to the accurate determination of its axis. In practice this eliminates the simple parabolic adjustment previously described and makes it necessary to draw a smooth irregular line through the computed curves which represents the best judgment of the analyst as to where the axis should be. In the case of permanent displacement the effect is even more serious.

At El Centro there was an obvious shift of the acceleration curve axis on the east-west component 19 sec after the start of the record. As the permanent displacement phase occurred in a very rough part of the record which on the velocity curve extended up to 12 sec the accurate selection of an axis was impractical although a typical permanent displacement pattern is indicated during the first five sec. On the north-south component of the velocity curve the permanent displacement pattern is not clearly evident and the curve is very complex. It is not too clear over the

30 sec of the record integrated whether shifting of the pendulum zero position occurred or not. The possibility of some error in separating the badly overlapping curves on the original accelerogram or the presence of undetectable zero shiftings of short duration can not be ruled out. There can be no confusion between these two sources of error when the zero shifting is of long duration, as in the cases previously discussed, because their effects are quite different.

In checking over the original El Centro analyses in retrospect new axis adjustments which seem reasonable would indicate approximately a five-inch movement of the ground to the north and a ten-inch movement to the west. This compares quite well with the eight- or nine-inch northwesterly movement indicated in the geodetic report. The first movement was about one inch in an opposite direction to the final displacement. This may have been a normal type of seismic wave superposed on the permanent movement which was accomplished in about two sec.

New suspension systems are now being installed in all the Survey's 52 accelerographs to eliminate the analytical difficulties here described. The sensitivities of many instruments also have been reduced and wider recording drums are being installed so that all records will be clearly legible. The recording of destructive seismic motion is practically a virgin field insofar as instrumental design is concerned, and recording equipment must be continually modified to keep pace with the phenomena revealed by every earthquake which is greater than any previously recorded.

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POLAR MAPPING APPLIED TO SEISMOLOGY

Leonard B. Lipson

Abstract--An indirect method of mapping is discussed by which the following problems on the surface of a sphere representing the Earth may be transferred to a normal zenithal stereographic projection and solved more readily and simply than by the use of trigonometric functions or other map projections: (a) Determination of great circle bearing of one position from another; (b) determination of great circle distance between two positions; (c) determination of unknown position when bearing and distance from another position are known; and (d) solution of triangulation of bearings problem from two or more positions to an unknown position.

Introduction--When points and curves on the surface of a sphere are projected onto a flat plane from the antipode of the point of tangency of the plane and the sphere, a stereographic projection of the points and curves is the result. When the point of tangency is on the equator, a normal zenithal projection results, and when the point of tangency is a pole, a polar projection results.

There are two properties of the stereographic projection which make it very useful. The first is that it is conformal, that is, the angle between any two curves on the sphere is equal to the angle between the projections of the curves on the projection or map. The second is that circles on the sphere project into circles or straight lines (circles of infinite radius) on the map. An excellent treatment of the proof of these statements is given by SOHON [see "References" at end of paper, 1932].

Polar mapping--A method of marking a normal zenithal stereographic projection was developed in the Engineering and Technical Service, Office of the Chief Signal Officer, in cooperation with Division 13.1 (Radio Direction Finding) of the National Defense Research Committee, which allowed it to be used to solve problems in spherical trigonometry by indirect methods of mapping. A projection of the latitude and longitude lines of a sphere is shown in Figure 1 and is marked in accordance with this development. It should be noted that this method is exact for a sphere, so that problems on the Earth may be solved by using geocentric latitudes.

The United States Hydrographic Office has available a stereographic projection (H. O. Misc. No. 7736-1) which is 16 inches in diameter, contains parallels and meridians in one degree intervals, and is quite suitable for use with the method of mapping under discussion.

In use, a transparent overlay is superposed on the projection or grid as it will be called from now on. The overlay serves as a map of the Northern Hemisphere, although in general this map will remain blank except for positions of interest in any particular problem. Since any position in the Southern Hemisphere can be represented by its antipodal point in the Northern Hemisphere, this method may be used to solve problems involving either hemisphere, or both.

The equator of the grid represents a meridian of the map. Since there is only one equator on the grid, only one meridian on the map can be operated on at a time. When it is desired to operate on a particular meridian, the map is rotated until the desired meridian coincides with the equator of the grid. The latitudes on that meridian are then given by the numbers on the meridians of the grid.

Referring to Figure 1, for positions of northern latitude, the numbers on the left half of the equator of the grid represent the parallels between the equator and the North Pole. For positions of southern latitude (in which case the antipodal points are actually mapped), the number on the right half of the grid represent the parallels between the equator and the South Pole.

The polar circle for any position is the circle traced by the poles of all the great circles passing through the position. For each point on the equator of the grid, the polar circle appears as the meridian having the same number (in slanting instead of block print) on the other half of the equator.

Determination of great circle bearing of one position from another--Consider two positions, P_1 and P_2, on the surface of the Earth whose latitudes and longitudes are La_1, Lo_1, and La_2, Lo_2,

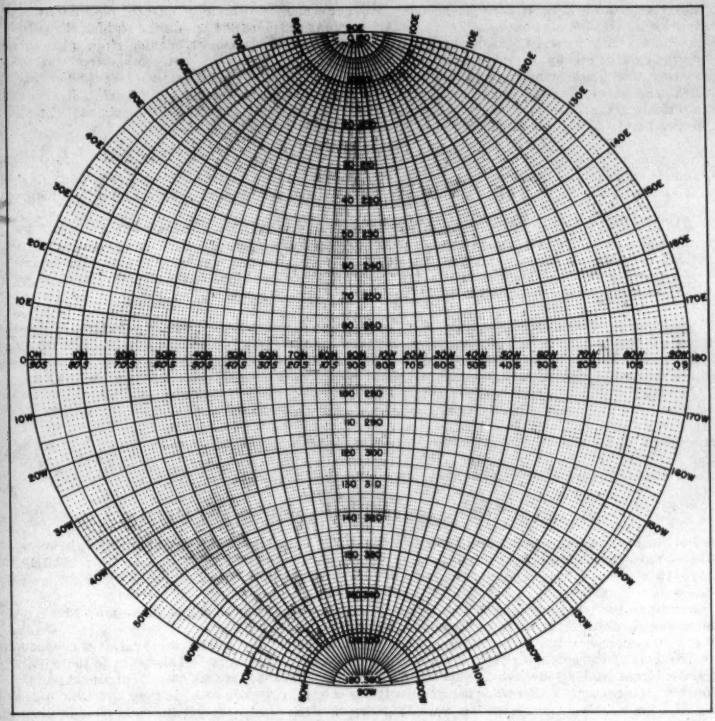

Fig. 1--A projection of latitude and longitude lines of a sphere

respectively (P_2 being west of P_1). If A is the bearing of P_2 from P_1, it can be shown by use of the sine and cosine law of spherical trigonometry that cot A = csc (Lo_2 - Lo_1) tan La_2 cos La_1 - cot (Lo_2 - Lo_1) sin La_1. All bearings are measured from north in a clockwise direction. Thus north is 0°, east is 90°, south is 180°, and west is 270°.

To illustrate the method, actual examples will be worked.

Problem: To find the great circle bearing of Strasbourg, France (48°24′N, 07°46′E) from Georgetown, D. C. (38°43′N, 77°04′W). First place a longitude index mark on the edge of the map. To plot the position of Strasbourg, rotate the map until the index is over 07°46′E, the longitude of Strasbourg. Now place a mark on the equator of the map at 48°24′N, the latitude of Strasbourg. Since the latitude of Strasbourg is north, the mark is placed on the left half of the equator. The mark is now considered to be the position of Strasbourg. The position of Georgetown is similarly plotted. It is known that through any two positions it is possible to pass only one great circle. The pole of this great circle is 90° away from both of the positions and thus is the intersection of the polar circles of the positions. To determine the pole of the great circle passing through Strasbourg and Georgetown, rotate the map until the positions, as plotted, lie along the same meridian on the left half of the equator. It is seen that this meridian is 53°2N. The pole lies on the right half of the equator at this same number in slanting print, and a mark is placed on the map at this point.

To determine the bearing of Strasbourg from Georgetown, rotate the map until the position of Georgetown is on the equator as when originally plotted. Observe the parallel on which the pole of the great circle between Strasbourg and Georgetown lies, and read the bearing from the numbers along the central meridian, which is 50°.5 or 230°.5. The true bearing is determined from the information of whether Strasbourg is east or west of Georgetown. Thus it is seen that the bearing of Strasbourg from Georgetown is 50°.5. To determine the bearing of Georgetown from Strasbourg, rotate the map until the position of Strasbourg lies on the equator and repeat the process. Thus it is found that the bearing of Georgetown from Strasbourg is 295°.1.

Determination of great circle distance between two positions--Again, considering two positions P_1 and P_2, it can be shown from the sine law of spherical trigonometry that $\sin P_1P_2 = \cos La_2 \sin (Lo_2 - Lo_1)/\sin A$. It is quite simple to solve the above problem by this method of mapping.

Problem: To find the great circle distance between Strasbourg and Georgetown. First plot the positions of Strasbourg and Georgetown as in the previous example. Next rotate the map until the positions lie along the same meridian. The distance in degrees can now be read along the central meridian between the parallels crossing this meridian at the positions of Strasbourg and Georgetown. This distance is thus found to be 58°.5.

Determination of unknown position when bearing and distance from another position are known--Consider a position P_1 from which the bearing A and the distance Δ to an unknown position P_2, the epicenter, are known. Galitzin [MACELWANE, 1936] has shown that A can be calculated from the ratio of the amplitudes of the east-west and north-south components. It can also be shown that

$$\sin La_2 = \cos \Delta \sin La_1 + \sin \Delta \cos La_1 \cos A$$

and

$$\cos (Lo_2 - Lo_1) = (\cos \Delta - \sin La_1 \sin La_2)/(\cos La_1 \cos La_2$$

This problem can also be solved quite simply by this method of mapping.

Problem: Georgetown, distance, 34°.6, bearing, 03°.8; and Strasbourg, distance, 40°.5, bearing, 333°.2. This information for the earthquake of November 20, 1933 at 23^h was taken from MACELWANE [1936]. The bearings were calculated by assuming the epicenter to be 72°.8N, 70°.2W.

First plot the positions of Strasbourg and Georgetown as in the previous examples. Now rotate the map until the position of Strasbourg is on the equator as when originally plotted. On the polar circle corresponding to Strasbourg, place a mark at the point where the parallel corresponding to the bearing of the epicenter from Strasbourg crosses the polar circle. This point is the pole of the great circle passing through Strasbourg at a bearing of 333°.2 and thus this circle must pass through the epicenter. Next rotate the map until the pole is on the equator on the right hand side of the grid. Since the pole lies over the point 73° N (in slanting print), the great circle passing through Strasbourg and the epicenter is the meridian marked 73° N on the left half of the equator. On this meridian place a mark 40°.5 above and below the position of Strasbourg. These are the two positions where the circle corresponding to a bearing of 333°.2 from Strasbourg crosses the circle corresponding to a distance of 40°.5 from Strasbourg.

By bringing each position, in turn, to the left half of the equator and reading the latitude under the position on the equator and the longitude under the longitude index mark, it is found that these positions are 72°.8N, 70°.2W, and 11°.2N, 24°.6E. Since the bearing is ambiguous, that is, it may be 333°.2 or 333°.2 - 180°, the true position has to be resolved from the false position by other means. One method of finding the true position is to utilize information from another station. Using the information from the Georgetown station for the same earthquake, it is found that the epicenter is 72°.8N, 70°.2W.

Solution of triangulation of bearings problem from two or more positions to an unknown position--The solution of this problem is similar to that just discussed except the distance to the unknown position is not known.

Problem: Georgetown, bearing 03°.8; and Strasbourg, bearing 333°.2. Determine the pole of the great circle passing through Strasbourg at a bearing of 333°.2 as in the previous example, as well as the pole of the great circle passing through Georgetown at a bearing at 3°.8. Now rotate the map until the poles lie along one of the meridians on the right half of the grid. This is the latitude of the unknown position or epicenter and is 72°.8N. The longitude index will be over the longitude

of the position which is 70°.2 W. The 180° ambiguity of the location of the position must be resolved by other means.

Note on accuracy--Errors may arise caused by inaccuracies in the construction of the grid. Thus any grid used will have to be taken on its own merits. The problems discussed were worked, using the projection which is available from the United States Hydrographic Office. Nonetheless, even with a grid eight inches in diameter, the errors should be less than those arising from other means.

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FOURIER ANALYSIS OF A BLAST RECORD

Carl Kisslinger

Abstract--This paper reports the Fourier analysis of a seismogram of a dynamite blast recorded by a Taylor-Macelwane seismograph. The first six harmonics were calculated for 26 sections of the record. The errors inherent in such an analysis are discussed.

Introduction--There occur in nature many phenomena which can be expressed by curves composed of a repetition of congruous parts at certain intervals. These phenomena have been termed "periodic," and may be represented analytically by a periodic function of a variable, that is, by a function such that $f(x + k) = f(x)$, where k is the period. The trigonometric functions sin x and cos x are such functions with a period 2π.

Any single valued trigonometric function can be expressed by an infinite trigonometric series, or Fourier's series of the form $y = f(x) = a_0 + a_1 \cos x + a_2 \cos 2x + \ldots a_n \cos nx + \ldots + b_1 \sin x + b_2 \sin 2x + \ldots b_n \sin (nx) + \ldots$, where the coefficients a_k and b_k may be determined if the function is known.

Method--To determine the coefficients of the unknown periodic function, the interval from $x = 0$ to $x = 2\pi$ is divided into n equal intervals and the first n ordinates measured.

The problem is then to determine the constants in the equation

$$y = a_0 + a_1 \cos x + \ldots + a_k \cos kx + \ldots + b_1 \sin x + \ldots + b_k \sin kx + \ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where the number of terms is n, so that the curve obtained by plotting the functions with the determined coefficients will pass through the n points measured. If the n sets of values for x and y that have been measured are substituted in (1), n linear equations in the a's and b's of the form

$$y_r = a_0 + a_1 \cos x_r + \ldots + a_k \cos kx_r \ldots + b_1 \sin x_r + \ldots + b_k \sin kx_r \ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

result, where r takes in succession the values $0, 1, 2, \ldots, n - 1$. These equations may now be solved for the coefficients. An outline of the solution is given by LIPKA [see "Reference" at end of paper, 1918].

Application--The periodic curve analyzed was a seismogram from a Taylor-Macelwane seismograph, recording the Earth vibrations generated by a sub-surface explosion of 175 lb of dynamite. It was sought to discover what frequencies of vibration of the Earth's surface make up the displacements recorded. The first six harmonics of the total displacement were computed.

The total length of trace was approximately 13.6 inches, which necessitated division into smaller sections to facilitate the analysis. The first section was taken from the first energy break to the next point along the zero displacement axis where the trace crossed the axis going in the same direction, that is, since the first energy break was in the negative direction, the first section ended at the next point where the trace crossed the zero axis going in the negative direction. The rest of the trace was divided in a similar fashion, each section ending on the zero axis. The result was 26 sections, starting at the first energy break and ending where the amplitude of the oscillations became indistinguishable.

Each of these 26 sections was analyzed separately according to the method outlined above. The instrument employed to make the ordinate measurements was a Gaertner Micrometer Microscope. This microscope, which can measure distances to 0.00001 inch, was originally built for tool design work, but finds a useful adaptation in the accurate measurement of amplitudes on seismograms. The field of the microscope contains crosshairs which can be set parallel to the motion of the stage, and turning the micrometer handles moves the stage of the instrument a distance which may be read directly in inches on the scales. An object on the stage will move in relation to the

crosshairs when the micrometers are turned, and distances along the object may be measured accurately.

The record was clamped on the stage in such a way that, when the stage was centered in the y direction and at zero on the time axis, the zero displacement axis of the record corresponded to the horizontal crosshair. Starting with the first section, the entire length of each division of the trace was measured and divided by twelve. Then the record was moved along the x, or time axis, a distance equal to 1/12 of the total length of the section and the amplitude at that point, corresponding to x = 30°, was measured. In this manner the first 11 ordinates were measured, the twelfth corresponding to 360°, or the first ordinate of the next section. In this manner the entire length of the record was traversed, so that in the end there were 12 measured ordinates for each of the 26 original sections.

Having measured the ordinates, it was then possible to compute the coefficients of the terms of the Fourier series for the first six harmonics. With these coefficients known, the individual harmonics could be plotted and summed at each point. The result of this summation should give a very close approximation to the original trace. In this problem the final curve did agree very closely, the discrepancies running in the order of 0.0002 or 0.0003 inch out of a total displacement of perhaps 0.15 inch. There were greater discrepancies which will be discussed latter.

With the harmonics of the trace plotted and summed, it may be stated that as regards the frequency of the energy represented in the seismogram, there were two definite and important phases.

The first energy to arrive was of high frequency and small amplitude. The fundamental period present was 0.046 sec, which was prominent for about the first half sec. This component was present as the fundamental in the first and second sections, as the second harmonic in the third section, and as the fourth harmonic in the fourth, fifth, and sixth sections. It disappeared after the seventh section, in which it was very weak. Also present in the first phase was a period of approximately 0.023 sec or 1/2 the fundamental.

The second phase made its definite appearance after 1/4 second. The fundamental period of the second phase was preceded at approximately 0.1 sec by energy with a period of 0.065 sec. This was present from this point to 1 7/8 sec. where it disappeared.

Toward the end of the record, after approximately 2 1/2 sec, energy of longer period, 0.212 sec appeared.

The small errors mentioned previously can be explained by the fact that the Fourier method of analysis is an approximation method, and other harmonics higher than the sixth may have been present.

There is one factor inherent in the method of analysis that accounts for the rather large errors that appear in a few scattered places through the record. The analysis assumes a fixed zero displacement axis, while actually in a seismometer of the pivot type, such as was used, the zero point of oscillation shifts as the natural pendulation of the seismometer comes into play. The greater part of this zero shift is taken care of by the oonstant term in each of the Fourier equations. The factor that cannot be compensated for in this manner is tilt of the zero axis. The slope of the axis produces a small error which, however, is cumulative because of the method of computation, and results in appreciable differences from the expected values of the ordinates, especially at x = 30° and x = 60°, and multiples of these angles.

One thing brought out by this study was the value of an accurate micrometer microscope for ordinate measurements, for Fourier analysis and for numerical integration problems.

A harmonic analysis carried out before a numerical integration of a seismogram will yield information on shifts in the zero axis that is otherwise unknown and not easily obtainable.

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DIRECTION RECORDING EQUIPMENT FOR THE GRINNELL WIND SPEED INSTRUMENT

Ronald L. Ives

Abstract--Equipment for recording wind direction to eight points on the chart of the Grinnell Wind Speed Recorder or a similar instrument is here outlined.

Introduction--Field recording of wind speed, to any accuracy attainable by the anemometer, and with a wide range of practicable time-constants, has been made possible by the development of the Grinnell condenser-discharge wind speed recorder [see "References" at end of paper, GRINNELL, 1945, pp. 6-8 and 24-25,].

Simultaneous recording of wind direction has been found somewhat difficult, four methods having found some favor [MIDDLETON, 1942; GRINNELL, 1945. pp. 9-10; IVES, 1947a; IVES 1947b]. Each of these methods, although having special merit for some special purpose, requires the use of a recording milliammeter and auxiliary equipment, so that the cost of recording wind direction equals that of recording wind speed, and the direction record requires nearly as much time, energy, personnel, and office space for its interpretation as does that of speed.

Although synchronization of the two record charts in the field can be attained by connecting the two recorder chart drives mechanically, use of two charts for the wind record increases the possibility of error markedly.

Standard chronograph pen arrangements--Because commercial recording milliammeters used in wind direction and speed recorders are normally equipped with chronograph pens which make a linear record at each margin of the main chart, methods of recording wind direction at the edges of the speed chart by use of these "edge pens" were reviewed.

When a discontinuous record of wind direction, to either eight or sixteen points, is suitable, a stepping-switch "hunter" actuated by the anemometer, may be used to record the wind source each N sixtieths of a mile (use of a 1/60 mile anemometer is assumed here). N is a number exceeding eight [IVES, 1947a]. This gives a record on one margin of the wind speed chart, using one edge pen, and leaving the other available for some other recording.

Where direction recording to four points is adequate, use of both edge pens will produce the desired record with no distinction between one recorded direction and "out of service." This arrangement is shown in Table 1. Note the ambiguity, with this arrangement, between S indication

Table 1--Arrangement using two edge pens

Direction	Left pen	Right pen
N	E	D
E	D	E
S	D	D
W	E	E
OS	D	D

E = energized, D = deenergized, and OS = out of service.

Table 2--Arrangement eliminating ambiguity

Direction	Left pen	Right pen
0° - 120°	E	D
120° - 240°	E	E
240° - 360°	D	E
OS	D	D

Notation as in Table 1.

and out of service indication. Although several variations are possible, all have this ambiguity at some position.

By decreasing the number of direction indications, and hence increasing the arc covered by each indication, this ambiguity may be eliminated, the arrangement being as in Table 2. With this

arrangement, there is a plain chart indication when the direction recorder is not working. Both of these systems require a special, although obvious, vane contacting system.

Special chronograph pen arrangement--As three or four point direction recording is inadequate for most meteorological work of an accuracy requiring a Grinnell speed recorder, or other instrument of comparable accuracy, the use of the regular chronograph pens as outlined in Tables 1 and 2 is somewhat restricted. In general, eight is the minimum number of direction points that should be recorded.

Direction recording to eight points is possible by use of two chronograph pens, each of which has three positions, as in Table 3.

Table 3--Use of two chronograph pens to record eight points

Direction	Left pen	Right pen
N	l	c
NE	l	r
E	c	r
SE	r	r
S	r	c
SW	r	l
W	c	l
NW	l	l
OS	c	c

l = pen at left, c = pen centered, r = pen at right, and OS = out of service.

This general principle is not new, bilateral pens having been used in wind direction recorders of commercial manufacture for some decades [MIDDLETON, 1942].

Several experimental pens were constructed, using, insofar as possible, standard commercial parts, as no bilateral edge pens were commercially available for the recorders that were used. A schematic diagram of one such pen (to fit the Esterline-Angus recording milliammeter) is shown in Figure 1. Although such a pen is a close fit in the recorder case, its construction entails no special skill. However, attempts to construct a pair of similar pens to fit into a General Electric Photo-electric Recorder were not very successful because of space limitations.

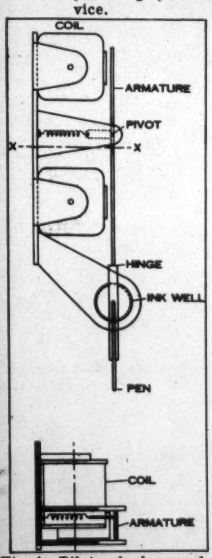

Fig. 1--Bilateral edge pen for wind direction recording at edge of wind speed chart

Bilateral edge pens require a special contacting arrangement in the wind vane. This is shown in Figure 2. Arrows on each contacting sector indicate the coil connection; LL indicates that the sector connects to the coil that pulls the left pen to the left; LR to the right, and similarly for other notations. Free ends of each coil connect together, and to the power supply (battery). The other side of the power supply connects to vane COM.

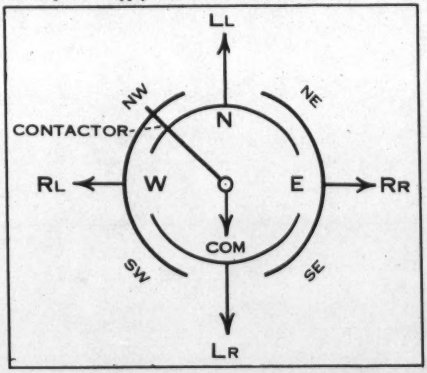

Fig. 2--Arrangement of vane contact sectors for eight point direction recording with bilateral edge pens

Conclusions--By use of bilateral edge pens, wind direction to eight points can be recorded on the same chart as the wind speed, thereby very markedly reducing the amount of equipment needed in the field and the amount of paper to be handled in interpreting the field records. Synchronization troubles are automatically eliminated by use of this type of recording, and chances for interpretation error are considerably reduced.

Acknowledgements--The writer is indebted to S. W. Grinnell of Stanford University for helpful discussions of direction recording problems, and for a stock of miscellaneous recorder parts with which experiments were conducted.

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COMPUTATION OF THUNDERSTORM RAINFALL

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Abstract--The rainfall of a "young" thunderstorm is shown to be expressible as the product of q_G, the average surface specific humidity of the air entering the storm, and C, the "convergence factor," which is a function of the cloud base dimensions and of the wind blowing into the region beneath the cloud. The equation may be applied to more involved storms, such as hurricanes or wave cyclones, as long as orography is not an important feature; in these cases the moisture factor is still easily determined, but the convergence factor becomes more difficult to evaluate.

For purposes of estimating the maximum possible thunderstorm precipitation it is shown that q_G and C may be maximized through statistical study of weather records. For the problem of quantitative precipitation forecasting two methods are suggested: (1) Substitution of forecasted values of moisture, wind, and cloud dimensions into the equation, and (2) forecasting of rainstorm types whose convergence factors are known, and forecasting of the surface specific humidity. The second method necessitates a rather lengthy investigation of the run-of-the-mill variety rather than of the excessively heavy rainstorms customarily studied by hydrometeorologists.

Introduction--Preparing an estimate of the maximum possible rainfall for a given location and during a given season is a problem very closely allied to quantitative forecasting of rainfall. The time element, alone, is the really significant difference between the two problems. When one estimates maximum possible precipitation he is simply forecasting the greatest amount of rain he believes might ever fall, but he does not say when it will fall. To all intents and purposes he is forecasting an asymptote which the day-to-day forecast may approach but may never reach. It appears only reasonable, therefore, that the weather forecaster should become familiar with estimates of maximum rainfall values. As will be seen later, the methods employed in arriving at the maximum figures can also be of use to the meteorologist concerned with quantitative precipitation forecasting.

In the field of hydrometeorology, estimates of maximum possible precipitation are frequently computed through development of equations into which the most critical combination of measurable variables is placed. There are two principal avenues of approach in the derivation of these equations. First, one may follow purely statistical procedures, making use of a large sampling of rainfall data to derive a regression equation. Second, the rainfall of a storm may be expressed in terms of an equation derived from such basic physical relationships as the equations of continuity, motion, and other factors. Sometimes it becomes necessary to combine the two methods with the result that a part physical, part statistical equation is developed. Even in the physical approach it usually happens that statistics must be applied for determination of boundary conditions and for checking the validity of the rainfall equation.

An approximate short-cut method can also be followed. Basically, this approach assumes that the rainfall equation is composed, first, of a factor M dependent only upon the moisture charge of the rain-producing air and, second, of a factor C which includes all other variables. The rainfall of a storm thus equals MC. For each important storm of record the value of M is determined through study of the pertinent weather maps. Through what is called the process of "moisture adjustment" the storm rainfall is increased by substituting for M a larger value which is representative of the maximum possible moisture charge which can occur at the storm location. Frequently one is concerned with deriving estimates of maximum possible rainfall over drainage basins which have experienced no major storms in their periods of record. Next is applied the process of storm transposition, in which the basic assumption is to the effect that certain storms which occurred elsewhere could just as well occur over the basin with their values of C unaltered. The transposed storms are adjusted to the maximum possible values of M for the basin, and an envelopment of the adjusted values produces the maximum possible rainfall estimate. It is apparent that a detailed, synoptic study of each storm is required for the determination of its area of transposibility. Again, exhaustive statistical analyses of past weather records must be made in order that maps showing the distribution of maximum possible moisture charge by months and by durations (6, 12, 18,...hr)

may be prepared. On such maps the moisture charge is customarily expressed in the form of surface dewpoint since, in major storms and, in particular, in the maximum possible storm, a saturated atmosphere with a moist adiabatic lapse rate is a good assumption. Most of the discussion which follows in this paper will be concerned with this transposition-adjustment technique, which is based upon the concept that the product of M and C expresses the rainfall of a storm.

A number of equations have been developed to determine rainfall quantitatively, some of which have had widespread use. One of these models, perhaps the most commonly used in the field of hydrometeorology and worthy of special note because of its conceptual simplicity, will be briefly outlined in this paragraph. A saturated, pseudoadiabatic atmosphere is assumed from ground to top. The cell is divided into three layers, with convergent inflow taking place in the lowest layer and divergent outflow in the top. The pressure at the top is assumed to vary from 300 mbs when the surface temperature (or dewpoint) is 50°F to 100 mbs at a surface temperature of 78°F. The rainfall is assumed to be proportional to the difference in precipitable water between the bottom and top layers, the constant of proportionality, in turn, being assumed to be completely independent of moisture. Under these assumptions it is apparent that the precipitable water difference, hence the rainfall, is a single-valued function of the surface dewpoint as far as the moisture elements of the cell are concerned. In this model the quantity M becomes the precipitable water difference. The techniques of transposition and adjustment can then be applied, although it should be remembered that the adjustment is that of moisture only. For purposes of moisture adjustment, the ratios of the pressure thicknesses of the three layers plays an insignificant part; for example, the adjustment factors are essentially the same whether one assumes that the three layers are equal in their pressure thicknesses or whether he assumes that the thickness of the central layer is zero. The dynamics of the storm is assumed not to be changed during the process, although the height of the cell top changes. Other techniques must then be followed in an attempt to maximize the storm's dynamics. This model has been discussed in detail in a recent report [see "References" at end of paper, HYDROMETEOROLOGICAL REPORT NO. 23, 1947].

Other models of storm rainfall which have been devised are usually more complicated than the above. All of them necessarily have limitations, either mathematical, physical, or both. For instance, most models, including the one just described, assume that through deep layers of air the wind-speed averaged with respect to pressure is the same as the wind speed averaged with respect to precipitable water. Further, moisture adjustments of certain storms through large ranges of dewpoint yield results which do not appear acceptable in the light of data now available. In the following will be derived a thunderstorm rainfall equation which is based upon a model defined by the actual shape of a typical thunderstorm cell, and it later will be shown that application of the underlying principles can be extended to certain storms of dimensions larger than those of a simple thunderstorm. The mathematical limitations have been reduced, and adjustments through large moisture ranges produce results which seem to have added consistency. However it has been necessary to introduce certain other physical assumptions. Consequently, this paper should be considered at the moment simply as a presentation of a different, and not necessarily better, method of computing rainfall quantitatively. Investigations are being carried on aimed toward a more positive evaluation of the several existent models.

The thunderstorm rainfall equation--It is necessary to make some general restrictions regarding the thunderstorm whose rainfall will be evaluated in terms of measurable variables. Only the earlier stages of the storm will be considered, that is, those in which there is an anvil present but in which the surface winds are still blowing into the storm center. In connection with this restriction, it is interesting to note that BRANCATO [1942], as a result of his study of the rainfall from a large number of individual thunderstorm cells, reports that the heaviest rain usually occurs within the hour after the beginning of rain from a thunderstorm. Again, acceleration terms are assumed to be negligible. The restriction is also made that there is no appreciable vertical shear of the wind in the vicinity of the thunderstorm, although a velocity of translation is permitted.

In Figure 1 is illustrated a typical thunderstorm cell; its tendency toward an hourglass shape is immediately apparent. Its shape, with a wide cloud base and anvil and with a constriction in the central regions, suggests that the walls of the cloud essentially define the outer streamlines of the vertical currents rising within the cloud. A similar conclusion as to the relation between flow pattern and cloud shape has been reached by BROOKS [1922] and other writers. Observations of the vertical distribution of humidity and temperature within convective clouds at times appear inconsistent with the concept that all of the air within a thundercloud enters through its base. STOMMEL [1947] reasons very convincingly that deviations from the moist adiabatic lapse rate can be attributed to entrainment of air from the environment into the sidewalls of the convective cloud. Accordingly, it will be assumed herein that the cloud walls define the outer limit of the upward-moving air, and that there is an organized entrainment which feeds moisture and air into the cloud through its walls.

Fig. 1--Typical thunderstorm cell

A schematic cross-section of a simple thunderstorm cell is given in Figure 2. The air from which most of the rain is produced flows into the cell between the cloud base (level B) and the ground (level G). Per unit time, therefore, the amount of air entering from below is equal to the product of the pressure difference ΔP_1 between levels G and B (divided by the acceleration of

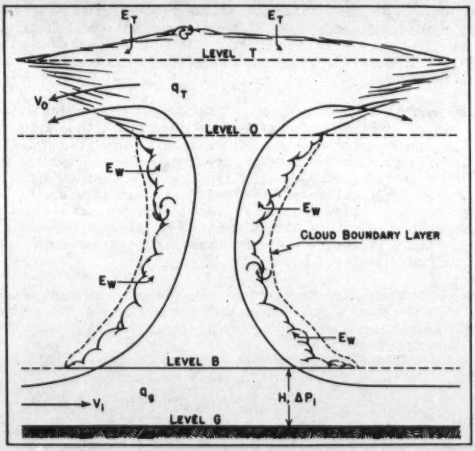

Fig. 2--Idealized, single thunderstorm cell

gravity g), the perimeter S_1 of the cloud base, and the average inflow wind component V_1 normal to the perimeter beneath the cloud. The transport of moisture is simply equal to the air transport multiplied by the average specific humidity of the air between cloud base and ground. To a good degree of approximation, the average specific humidity below the cloud will equal the value q_G of this element at the ground. It must be emphasized that the early stages of development

of the thunderstorm cell are being considered. It has been shown by BYERS [1947], BRAHAM [1947], and their collaborators that in the later stages of a thunderstorm's history downward currents within the cell result in outflowing winds at certain locations beneath the periphery of the cloud base.

Up to the height (level 0) at which the thunderstorm anvil begins, the walls are typically bulbous. Since it is actually a vertical jet through an essentially still environment which is being considered, it is a logical conclusion that the "cauliflower" structure is the visible manifestation of eddies formed along the borders of the jet. There will thus be a turbulent exchange of both air and water vapor along the walls; furthermore, a certain proportion of the cloud droplets near the walls will be carried outside by turbulent motion and will evaporate into the air immediately surrounding the cloud. If the air of the environment is dry, evaporation will occur quickly and the cloud walls will be sharply defined to the eye. On the other hand, if the surroundings are near saturation, evaporation will be slow and haziness will be apparent in the neighborhood of the cloud. Observations made by airplanes entering convective clouds have shown that turbulence is very small, or absent, until the walls of the cloud are penetrated. For the purposes of the present derivation, lack of appreciable turbulence in the region outside of, but close to, the cloud walls will be assumed always to be the case. In view of this assumption there will be defined a cloud boundary layer, lying just outside of the cloud, within which the turbulence damps out and across the outer walls of which there is only a very small gradient of water vapor. In the case of the nearly saturated environment the haziness lies within the boundary layer. Turbulent, unorganized exchange of air and moisture across the outer walls of the boundary layer must be on a very small scale, conceivably approaching that of molecular diffusion, and will probably be overshadowed by the organized entrainment which may exist. The total gain of air through entrainment along the cloud walls, in grams per unit time, may be called E_w. If the proportionality between environment moisture and surface moisture is represented by k_1, the total gain of moisture through the cloud walls becomes $k_1 E_w q_G$.

Very little is known at present of the structure of the top of a thunderstorm anvil. Since the upward growth of a thunderstorm is usually limited by a pronounced temperature inversion (sometimes, perhaps, by the tropopause), the top is likely to be rather smooth. Without much doubt, purely turbulent exchange of air and moisture across the cloud top must be very small. There may be, however, a certain amount of entrainment. If E_T represents the total mass of air entrained into the top of the anvil per unit time, then the total moisture crossing the top becomes $k_2 E_T q_G$. Here, k_2 is a constant of proportionality between the moisture content of the air above the cloud and that of the air at the ground.

The anvil of a thunderstorm typically displays a fibrous appearance, the winds at those levels seemingly blowing outward with the droplets of the anvil cloud evaporating at its walls. The assumption is accordingly made that above level 0 (the base of the anvil) the organized, sidewall entrainment and the unorganized, turbulent exchange are replaced by an organized outflow from the cloud measured by the velocity V_0. The total outflow of air along the anvil sides is thus the integral, from 0 to T, of $SV_0 dP/g$, and the outflow of moisture is the same quantity multiplied by q. In the expression for moisture outflow the average value of q, written as $\bar{q}_T$, may be taken outside of the integral. It should be remembered that the average is made with respect to the variable $SV_0 dP/g$, which means that $\bar{q}_T$ is a value probably, although not necessarily, representative of the specific humidity closer to level T than to level 0.

From the above definitions and assumptions the conditions for continuity of air can very simply be stated: the air leaving the anvil is equal, all per unit time, to the air entering the region beneath the cloud base, plus the air added to the cell by entrainment along the sides and at the top. In equation form, this statement becomes

$$\int_0^T (SV_0/g)dP = S_1 V_1 \Delta P_1/g + E_w + E_T \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

It can also be said that the moisture leaving the anvil is equal to the moisture entering the region below the cloud base, plus the moisture gained by the cell through entrainment along the sides and at the top, minus the rain which reaches the ground. If R is the average depth (actually a mass, but expressible in terms of inches) of rain falling per unit time over the area A beneath the cloud, the equation of continuity for moisture is, therefore,

$$\bar{q}_T \int_0^T (SV_0/g)dP = (S_1 V_1 \Delta P_1/g)q_G + k_1 E_w q_G + k_2 E_T q_G - RA \quad \ldots\ldots\ldots\ldots (2)$$

The integral terms may be eliminated through combination of these two equations, whence the resulting "thunderstorm rainfall equation" becomes

$$R = [(S_1V_1\Delta P_1/g)(q_G - \bar{q}_T) + E_w(k_1q_G - \bar{q}_T) + E_T(k_2q_G - \bar{q}_T)]/A \quad \ldots\ldots\ldots (3)$$

This equation is quite similar to one derived by SHOWALTER [1944], who expressed rainfall intensity as a function of the vertical velocity component, air density, and mixing ratio at the condensation level, and the mixing ratio at the top of a convective updraft.

If one were able to forecast all of the independent variables contained in (3), he could forecast the rainfall. In particular, if the maximum possible values of the variables or, more correctly, the most critical combination of them, could be determined, the physical upper limit of thunderstorm rainfall could be stated with considerable assurance. At the present moment such cannot be done with exactness. Nevertheless, it is possible to make certain approximations which will simplify the equation and make it more adaptable to solution of the problem of thunderstorm-rainfall computation.

Estimation of maximum possible thunderstorm precipitation--The value of the specific humidity $\bar{q}_T$, a quantity measured near the top of a thundercloud, will be small compared with q_G, the specific humidity at the ground. For a rough approximation, then, $\bar{q}_T$ can be neglected in rainfall calculations. For the purpose of moisture-adjusting major storms of record, however, it is not necessary to resort to such a measure. Instead, a constant of proportionality, k_3, between the two humidity values may be introduced into (3) which then becomes

$$R = \left\{[S_1V_1\Delta P_1(1 - k_3)/g + E_w(k_1 - k_3) + E_T(k_2 - k_3)]/A\right\}q_G \quad \ldots\ldots\ldots (4)$$

In the moisture-adjustment technique the end product is an estimate of the rainfall of a storm were its moisture charge to be raised to the greatest possible value. Equation (4) provides a means of deriving such an estimate. In this equation, q_G is the only independent variable concerned with the moisture charge of the rain-producing air. Of the other terms on the right-hand side some are concerned with the dimensions of the cell (S_1, ΔP_1, and A), some with air movement (V_1, E_w, and E_T), and the rest with the moisture stratification within and outside of the cloud (k_1, k_2, and k_3). To apply the equation it is necessary to assume that the prescribed combination of these elements would remain unchanged were q_G to be raised to its maximum possible value. Within the braces of (4), these elements comprise a quantity which may be called the convergence factor C, whereupon a simplified moisture-adjustment equation may be written

$$R = Cq_G \quad \ldots\ldots\ldots (5)$$

The invariance of certain of the components of C is more a matter of definition than of assumption. For instance, the whole concept of moisture adjustment is based upon a constancy of such quantities as wind flow and cloud-base area in both the observed and adjusted storms. There are, however, certain inconsistencies in a definition which embraces all of the components. If the vertical cell dimensions do not change, it is not possible for k_3 to remain constant during an adjustment process since the slope of the moist adiabat representing the cloud moisture stratification must vary with q_G. Again, with an increase in q_G there must be released an additional amount of latent heat of condensation, and it is conceivable that all of the extra heat could be converted into kinetic energy. The addition of kinetic energy, in turn, would necessarily produce variations in the air-movement components: V_1, E_w, and E_T.

Except in the cases of extremely small storms or of storms in which the inflow wind is very light (in both of which cases the volume of rain would be insignificant), rough computations demonstrate, fortunately, that the error introduced through neglect of the additional latent heat energy is only a few per cent in magnitude. The error which arises from the fact that $\bar{q}_T$ increases more rapidly than q_G can also be shown to be small. More fortunately yet, the two errors act in opposite directions. When q_G is increased, the additional latent heat energy would undoubtedly act to produce more rainfall than computed, but the more rapid increase of $\bar{q}_T$ would serve to increase the water vapor transport out of the anvil sidewalls and hence to produce less rainfall than computed. The assumption must thus be made that these two effects, each of which is small, are equal and opposite in order that there may be consistency in the definition that C remains constant during a moisture-adjustment process.

The quantity R is the average depth of rain falling from the cloud per unit time. Since, during a moisture-adjustment process, the storm dynamics and dimensions have been held constant, it is reasonable to assume that the pattern of rainfall will also be unchanged. In other words, if R is the rainfall of a storm whose surface specific humidity was q_G, and R′ is the rainfall which should be expected were the specific humidity to be raised to its maximum possible value q_G', then the

isohyets in the maximum case would be the isohyets of the actual storm relabelled through multiplication of the actual values by the ratio q_G'/q_G. If the convergence factor of the storm of record happened to be near its highest possible value, the quantity R' becomes a good estimate of the maximum possible thunderstorm rainfall at the location under consideration.

As close an approximation as possible of the upper limit of the convergence factor is necessary for proper application of the moisture-adjustment technique. A detailed statistical analysis of the quantities which go to make up C would be very useful, but the time and difficulties involved in making such an analysis would be prohibitive. However a shorter procedure can be followed through consideration of the hundreds of storm rainfall studies already prepared by hydrometeorologists of the United States Weather Bureau and Department of the Army, Corps of Engineers. From each such study may be extracted the maximum average depth of rain which fell over a given area during a given length of time, for example, the largest 48-hour depth for any 100 sq mi area within each total storm area. These values may be plotted as ordinates against the respective values of q_G as abscissae, whence it is obvious that the slopes of the lines connecting the points with the origin are equal to the respective values of C. If there is a large sampling of storms and, furthermore, if the storms include major rain-producing ones, the slope of the envelope becomes an estimate of the maximum possible value of C.

The technique outlined above has been followed for several combinations of area and duration, in many instances the data being taken from storms of other than the simple thunderstorm type. Use of general-storm data in the present analysis will be justified in a later section. Figure 3 illustrates the scattering of points for an area of ten sq mi and a duration of 48 hr. The tendency of the values to possess an envelope consisting of a straight line through the origin is apparent. In the neighborhood of 200 major storms were used in this study, although most of those storms whose points lie well below the envelope have not been entered for the sake of simplicity. When the storms whose rainfall values were used here were originally selected for analysis of their depth-area-duration relationships, it was the practice to concentrate on the storms which produced large rainfall depths. As a result, there is a much smaller sampling of analyzed storms with low depths, and this fact comes to the surface in Figure 3 in which there are more values near the envelope at high precipitation amounts than at low ones. All of the storms used in this paper occurred eastward from central New Mexico, Colorado, Wyoming, and Montana. Storms were selected only when the ground over which they occurred was relatively flat, since the cloud-base parameters contained in the convergence factor C are not readily adaptable to storms occurring over steep mountain slopes. All seasons are represented. At the present moment, however, only areas up to 500 sq mi and durations up to 48 hr have been considered in the study of which Figure 3 represents one area-duration combination.

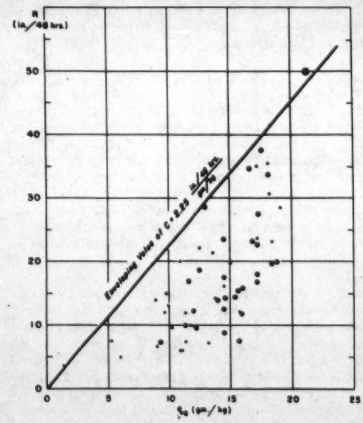

Fig. 3--Relation of R to q_G, area ten sq mi, duration 48 hr; values enclosed with a single circle were observed during July, August, and September; the value doubly encircled is an approximation of the world-record 48-hour rainfall amount

A point of particular interest can be approximately located on Figure 3. The world point-rainfall record for 48 hours is 63.6 inches, an amount which fell at Cherrapunji, India, on June 14-15, 1876. The average depth of rain over a ten sq mi area will generally be less than that of the rain gage which measures the peak amount within those ten sq mi. For the sake of illustration, a factor of 0.8 has been used to reduce the point value to a ten sq mi value of about 50 inches. The maximum possible storm dewpoint (statistically determined) which can persist for at least 12 hr anywhere in the United States is 78°F, along the Gulf Coast. If it is assumed that such a dewpoint persisted at Cherrapunji for 48 hr, a depth of 50 inches can be plotted against q_G of 20.5 gm/kg on Figure 3 as a very rough estimate of the world record value. Although the computation is approximate, it can be seen that the world record value, if the actual ten sq mi depth and the actual q_G were known, would lie reasonably close to the plotted point (doubly encircled in Fig. 3)

which is rather close to the upper end of the enveloping line representing the limiting value of C as determined from United States data.

In order that a comparison may be made between various combinations of area and duration, the rainfall depths, which already represent average values over the respective areas, must be divided by duration whence they become expressible in units of average depth per unit time. The enveloping values of C, modified in this way, for durations of six and 48 hr, and for areas of ten and 500 sq mi, are given in Table 1. The modified, enveloping values of C behave as might be expected, that is, they decrease as both area and duration increase, which means that the most effective convergence mechanism seems to exist only for a short period and over a small area. For the high values of C which can be computed from the points plotted in Figure 3, it is seen that variation of q_G is very important. BYERS [1947] has shown that variation in rainfall in the summer storms of Florida is mostly attributable to variations in the convergence factor. Such a circumstance very likely is true in nearly all locations when all storms, including those that produce inconsequential rainfall, are considered. It is when the maximum storms, whose values of C are of about the same magnitude, are under consideration that the moisture charge of the air becomes of importance.

Table 1--Modified C values, selected combinations of area and duration

Area	Duration	
	6 hours	48 hours
sq mi		
10	280	47
500	143	41

The question naturally arises as to whether there exists any orderly distribution of C with latitude and longitude. In Figure 3 no attempt had been made to differentiate geographically. However, the value of C, in units of inches of rainfall per gram of water vapor per kilogram of air, has been computed for each point and plotted on the map illustrated in Figure 4. The month of each storm occurrence has also been entered. A few isolines of C have been drawn on the map, a fairly close envelopment of the data being followed. A tendency toward a systematic relation between the convergence factor and location on the map can be recognized. For example, there is a definite decrease of C with latitude. Again, there is a pronounced tongue of high convergence extending northward from central Texas, and another along the eastern seaboard. The "island" of high convergence south of Lake Erie is caused by the occurrence of one storm in which warm, moist air flowed up the Ohio River Valley and precipitated a large part of its moisture in northwestern Pennsylvania. There is a marked absence of high values of C in the Mississippi Valley. Absence of such values should not, however, be associated with frequency of storm occurrences, as there are many instances of fairly high depths of rain in this Valley. Figure 4 contains only the top values of C. In a study of rainfall intensities expressed by the formula $i = c/t^n$, where t was duration, and the coefficient c and the exponent n were functions of geographical location, BERNARD [1930] discovered patterns in the central United States which are quite similar to that of Figure 4. He found, for example, that there was a pronounced trough of low values of c along the Mississippi and lower Ohio Rivers and a ridge of high values extending northward from eastern Texas and Oklahoma. There was also a definite decrease of c with latitude. The variation in c was quite large, the maximum values exceeding twice the minimum values. On some of his maps the distribution of n supported that of c, on others it did not. The variation of n, however, was much less significant than that of c.

It is more difficult to separate out the effect of season upon C. For instance, most months are represented among the values which define the western tongue of strong convergence in Figure 4. That the highest values are not necessarily found in summer is illustrated in Figure 3, where the points for storms which occurred in July, August, and September are encircled. Attempts are being made to determine any systematic behavior of C with respect to season.

Figure 4 contains a rather close envelopment of the values of C for storms which have not been transposed. Before the map could be used in estimating maximum possible 48-hour precipitation over ten sq mi, the effect of season would have to be taken into account. As an example, the high value of C in southeastern Alabama occurred in a March storm with a moderately low value of surface dewpoint. It is not believed that the dynamics of this storm, involving the polar front, could be reproduced in summer when the highest dewpoints can occur. Furthermore, each storm must be examined for its transposition potentiality. For example, the storm centered on the Gulf Coast of central Louisiana was a hurricane, and it is considered that incidence of similar rainfall from a similar hurricane could occur along nearly the entire length of the Gulf Coast.

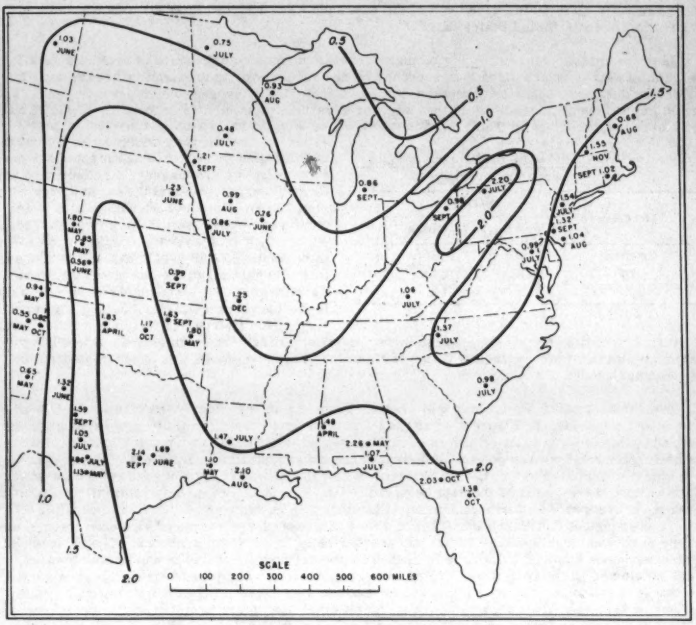

Fig. 4--Map of C, area ten sq mi, duration 48 hr

Adjustment of storms other than of the simple thunderstorm type--The derivation of the thunderstorm rainfall equation contains the assumption of a well-developed, yet not disintegrating, thunderstorm cell. However, observations frequently show that heavy rain may be falling from a thunderstorm beneath which the winds appear to be blowing radially outward. In such cases the cell is probably in its decaying stages, and rain previously held in suspension by ascending currents is no longer being suspended and is falling to the ground. Nevertheless, since the production of rain in the early stages was proportional to the surface specific humidity, it is likely that the amount of rain held in suspension is also roughly proportional to that value, so there is probably sufficient safety in the assumption that the rainfall in a decaying storm is proportional to the surface specific humidity. If this is so, then the thunderstorm rainfall equation may be applied to a thunderstorm regardless of its stage of development.

Using reasoning similar to that of the preceding paragraphs, it is possible for one to consider the general storm; the storm of large dimensions, such as a hurricane or a wave cyclone. The storm cell will be defined as the outer walls of the cloud system, however massive or complicated this system may be. An element of area of the cloud surface, whether it be along the sides, at the top or at the cloud base, will be given as da. The component V_i, perpendicular to da, of the wind flowing into the cell will probably, although not necessarily, be confined mostly to the lower levels. Similarly, the outflowing wind component will be expressed as V_o. Corresponding subscripts are given to q, the specific humidity. If the air density is designated as ρ, and if A is the area over which the rain R falls, then

$$\bar{q}_i \int_i \rho V_i da - \bar{q}_o \int_o \rho V_o da - RA = 0. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

is the equation of moisture continuity.

Two proportionality constants are introduced with the equations $\bar{q}_i = k_4 q_G$ and $\bar{q}_o = k_5 q_G$, where q_G is the surface specific humidity of the warm air mass entering the cloud system. Thus (6) transforms into

$$R = [(k_4 \int_i \rho V_i da - k_5 \int_o \rho V_o da)/A] q_G \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

which, of the same form as (5) in which the moisture factor has been separated from the convergence factor, is directly applicable to the process of storm moisture adjustment. It is of interest to note that only the moisture continuity equation, and not the equation of continuity for air, is necessary in the development of the moisture-adjustment equation. Here, the only assumption is (1) that of a steady state, in which there is no net accumulation of water vapor or liquid water within the cell. To proceed with the moisture-adjustment process, it is also necessary to assume (2) that all dimensions of the storm cell, the moisture stratification outside of the cell, and the shape of the isohyetal pattern remain unaltered in the adjustment process, and (3) that the small error in computed rainfall caused by neglect of latent heat considerations is counterbalanced by the small error introduced by neglect of the change in lapse rate, as q_G is changed, of the air within the cloud. With these assumptions, the equation $R = Cq_G$ may be used in the moisture-adjustment processing of any storm, regardless of shape or size, as long as the terrain is relatively level.

In regions where orography is significant, topographical features undoubtedly play a fundamental part in determining the dimensions and wind system of a storm. Moisture adjustments "in situ" can be made in mountainous terrain, but the technique of storm transposition cannot be applied except in the very rare cases where the terrain of the storm occurrence is nearly identical to that of the region to which it is desired that the storm be transposed. Over mountainous areas, much more elaborate techniques than use of (5) must normally be followed.

Quantitative thunderstorm precipitation forecasting--In a general review of the problem of forecasting rainfall quantitatively, SHOWALTER [1944] presented a number of equations in which forecastable variables can be placed to derive an estimate of expected rainfall amounts. To these may be added another, an equation applicable to quantitative forecasting of the rainfall from thunderstorms, which is quite similar to those derived by Showalter. If the cloud ceiling H is given in thousands of feet, the duration D in hours, the surface q_G and cloud top $\bar{q}_T$ specific humidities in units of gm/kg, the diameter d of the cloud cell base in miles and the average speed V of the wind blowing into the cell beneath the cloud base in MPH, (3) may be approximated as

$$R = 0.061DVH(q_G - q_T)/d \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

This equation, based upon a surface air density of 1.28×10^{-3} gm/cc, assumes that the bottom of the cloud is approximately circular. It also assumes that turbulent exchange and entrainment of air and moisture along the cloud walls are negligible. The latter assumption can be evaluated with the method of Stommel at such time that measurement of temperature and humidity within convective clouds becomes reliable. In order to make use of the equation, one must forecast the average values, over the duration D, of the inflow wind, cloud ceiling, cloud base diameter, surface specific humidity, and height of cloud top (in order to obtain the quantity q_T). The value of q_T, while not exactly the same as the $\bar{q}_T$ of (3), is a sufficiently close approximation. As a matter of fact, if the cloud top is expected to be very high, q_T may be completely neglected.

As an example of the use of (8), the meteorologist may forecast a surface specific humidity of 20.0 gm/kg, a ceiling of 1000 feet and a cloud top of 30,000 feet. An adiabatic chart then enables him to arrive at a value of 3.2 gm/kg for q_T. He may then forecast that the average inflow wind will be ten MPH and the cloud base diameter six miles. If the meteorologist expects that these will represent average values over a six-hour duration, the equation produces a forecasted value of 10.2 inches of rain as the average depth over the area beneath the cloud base. It should be borne in mind that R is the amount of rain falling from the cloud base and, in the event that there is a velocity of translation, in general the average depths over an area fixed with respect to the ground will be less. A rough adjustment to account for the storm translation is easily applied, however, through use of an equation discussed by Brancato. In the above example, the forecaster may expect the thunderstorm to move with a speed U. For computation of the average depth over an area of d miles in diameter fixed with respect to the ground, the depth R should be divided by the quantity $(1 + 4UD/\pi d)$, where D, as before, is duration.

Equation (8) is applicable to thunderstorm cells of small horizontal dimensions. When larger storms, such as wave cyclones, are being considered, the applicability of the simple equation is open to question. With proper analysis and arrangement of available rainfall data, however, it is

possible to make use of a combination of (5) and the concepts of storm transposition and moisture adjustment. In this case the forecaster would be dealing not with maximum possible storms, but rather with the run-of-the-mill variety. The equation to be used would be

$$R' = Rq'_G/q_G \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

in which R and q_G are the rainfall and surface specific humidity of an already-analyzed storm of record of the synoptic type which the forecaster expects to be repeated, and q'_G is the forecasted surface specific humidity.

The above method of transposition-adjustment forecasting is really a variation of the frequently used system of analogue forecasting, and suffers from the same defects. For results of any degree of reliability to be obtained, the forecasting of the storm type must be quite accurate. An error in the forecast of the surface specific humidity generally would not affect the accuracy of the result as much as an error in anticipation of the storm class. As a practical operating difficulty, samples of all types of storms, for all seasons and for all sections of the country, would have to be analyzed with respect to their depth-area-duration relationships and water vapor charges. At the present stage of development of the science of meteorology, therefore, it is likely that this system of rainfall forecasting would not be generally practicable. As more and more storms are analyzed hydrometeorologically, nevertheless, and as proficiency in forecasting large-scale wind systems increases, this method of quantitative precipitation forecasting shows promise in view of its simplicity and its ability to integrate so many of the variables involved in the production of rainfall.

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THE TWO NON-PARALLEL LAYERS PROBLEM ACCORDING TO THE NEW DEVELOPMENT OF THE POTENTIAL DROP RATIO METHOD OF THE ELECTRICAL PROSPECTING

Alfonso de la O. Carreño

At the meeting of the American Geophysical Union in 1944, I described a new alternate of the potential drop ratio method of the electrical prospecting [see "References" at end of paper, DE LA O., CARREÑO, 1944]; on that occasion I also described the two already known alternates and finished my study by an application of them and the new one to the problem of two parallel layers. In this paper I give a description of the solution of the two non-parallel layers problem according to the new alternate method. Geologically this condition may arise, for instance, when a rocky flank is covered by a sedimentary material, the free surface of which is horizontal or has a uniform slope.

Let us remember here that if, beginning from a point-electrode E on the ground (see Fig. 1), the potential drop ratios are measured between three electrodes ACB, keeping a fixed ratio $R = r_m/a_m$ for the successive positions of them, the observations will remain interrelated, also the various electrode spacings are as follows:

$$a_m = a_A = a_o \left(\frac{R+0.5}{R-0.5}\right)^m \quad \ldots\ldots (1)$$

$$a_{m+1} = a_B = a_o \left(\frac{R+0.5}{R-0.5}\right)^{m+1} \quad \ldots\ldots (2)$$

$$r_{Am} = a_o \left(\frac{R+0.5}{R-0.5}\right)^m (R-0.5) \quad \ldots\ldots (3)$$

$$r_m = a_o R \left(\frac{R+0.5}{R-0.5}\right)^m \quad \ldots\ldots (4)$$

$$r_{cm} = a_o \left(\frac{R+0.5}{R-0.5}\right)^m (R+0.5) \quad \ldots\ldots (5)$$

$$r_{Bm} = a_o \left(\frac{R+0.5}{R-0.5}\right)^{m+1} (R+0.5) \quad \ldots\ldots (6)$$

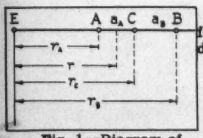

Fig. 1--Diagram of electrode spacing

Otherwise supposing that the other primary point-electrode is very far away, we have the following general expressions (1) The potential drop between A and C is

$$\Delta V_{AC} = \frac{\rho_a I (r_c - r_A)}{2\pi r_A r_c} \quad \ldots\ldots (7)$$

ρ_a is the resistivity of the semi-infinite medium under the ground surface. The potential drop between C and B is

$$\Delta V_{CB} = \frac{\rho_a I (r_B - r_c)}{2\pi r_c r_B} \quad \ldots\ldots (8)$$

The potential drop ratio for the central point C is

$$\frac{\Delta V_{AC}}{\Delta V_{CB}} = \frac{r_B (r_C - r_A)}{r_A (r_B - r_C)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The author demonstrated in the study mentioned before that for the new alternate method the normal ratio is constant, and has the value as given in (10)

$$F = \frac{r_B a_A}{r_A a_B} = \frac{R + 0.5}{R - 0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Equation (7) can be changed into the following one if the values of r_A and r_C are substituted in the function for the middle distance between A and C

$$\Delta V_{AC} = \frac{\rho_a I (r_C - r_A)}{2\pi r_A r_C} = \frac{\rho_a I}{2\pi a \left[\left(\frac{r}{a}\right)^2 - \frac{1}{4}\right]} \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

From (11) are deduced the two general expressions of (12) for the apparent resistivity

$$\rho_a = \frac{2\pi r_A r_C}{r_C - r_A} \left(\frac{\Delta V_{AC}}{I}\right) = 2\pi a \left[\left(\frac{r}{a}\right)^2 - \frac{1}{4}\right] \frac{\Delta V_{AC}}{I} \quad \ldots\ldots\ldots\ldots\ldots (12)$$

In the case of the author's alternate method, (12) can be expressed by (13)

$$\rho_a = 2\pi a_A \left(R^2 - \frac{1}{4}\right) \frac{\Delta V_{AC}}{I} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Let us see the theoretical form which (7), (8), (9), and (13) take in the application we are going to study

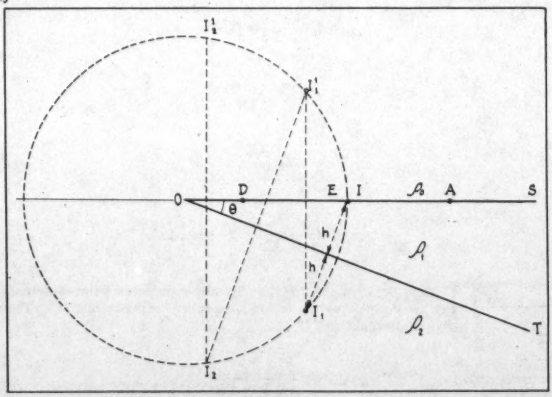

Fig. 2--Illustration of the analysed case

We have three different mediums characterized by their resistivities ρ_0, ρ_1, ρ_2, and the boundaries OS and OT (see Fig. 2), which intercept in O, at an angle θ. Let us suppose the point-electrode E, in the surface of separation OS, from which emerges a stationary or quasi-stationary electrical current I. The first part of the problem consists in computing the value of the potential

in any point on the surface OS; such a point can be in any direction from E. Of all these positions there are three more interesting than the other ones, and they are the following:

First case--The point A is at the right of E in a normal line to the intersection of the dihedral in O and which passes by E, that is, in the down-slope direction.

Second case--The point D is in the same position mentioned above, but on the left of E, that is, in the up-slope direction.

Third case--The point is in a line parallel to the intersection of the dihedral line which passes through E. In the figure, this point would appear to coincide with E.

Fourth case--A is to the left of O.

It is easy to see, as was demonstrated by ALDREDGE [1932-1936] and JAMESON [1941], that the images of I, originated by the surfaces OS and OT, remain in points on a circumference which has its center in O, whose radius is the distance OE and which lies in a plane normal to the dihedral in O and contains the point E. Because the inclination between OT and OS is θ, the angle measured from this surface to the images $I_2I'_2$ will be 2θ; to the following ones $I_2I'_2$, 4θ and thus successively, so that the limit of these succesive angles will be $\pi/2$ because we suppose that the surface OT ends in O. This means that the number of images is not infinite as in the case of the two parallel layers, but is limited by the value of the multiple angle $2n\theta \leq \pi/2$.

The maximum number of inferior images will be $n = \pi/4\theta$, and the same applies to the superior images; that is, the total of images will be $2n = \pi/2\theta$.

If $K_0 = (\rho_0 - \rho_1)/(\rho_0 + \rho_1)$ and $K_2 = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ are the reflection coefficients at the boundaries OS and OT, the intensity of the successive images will be

$$\begin{array}{ll} I_1 = K_2 I & I'_1 = K_2 K_0 I \\ I_2 = K_2^2 K_0 I & I'_2 = K_2^2 K_0^2 I \\ I_3 = K_2^3 K_0^2 I & I'_3 = K_2^3 K_0^3 I \\ \hline I_n = K_2^n K_0^{n-1} I & I'_n = K_2^n K_0^n I \end{array} \quad \ldots\ldots\ldots\ldots\ldots (14)$$

If the resistivity ρ_0 of the superior medium is infinite as in the case of the atmosphere $K_0 = 1$, the corresponding superior and inferior images, will be the same, that is

$$\begin{array}{l} I_1 = I'_1 = K_2 I \\ I_2 = I'_2 = K_2^2 I \\ \hline I_n = I'_n = K_2^n I \end{array} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

If the successive distances of the point A to each pair of images are, $r_1, r_2, \ldots r_n$; r_0 corresponding to the point-electrode E, the potential in A will have the general expression given in (16)

$$V_A = \frac{\rho_1 I}{2\pi}\left[\frac{1}{r_A} + 2\left(\frac{K_2}{r_1} + \frac{K_2^2}{r_2} + \frac{K_2^3}{r_3} + \ldots + \frac{K_2^n}{r_n}\right)\right] =$$

$$V_A = \frac{\rho_1 I}{2\pi}\left(\frac{1}{r_A} + 2\sum_{n=1}^{n=\frac{\pi}{4\theta}} \frac{K^n}{r_n}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

The successive distances from A to the images can be expressed as follows (see Fig. 3) for the three mentioned cases

$$
\begin{aligned}
r_1^2 &= \left(r_A \pm l_1\right)^2 + L_1^2 \\
r'^2 &= \left(r_A \pm l'\right)^2 + L_1^2 \\
r_3^2 &= \left(r_A \pm l_3\right)^2 + L_3^2 \\
\hline
r_n^2 &= \left(r_A \pm l_n\right)^2 + L_n^2
\end{aligned}
\qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)
$$

The plus sign applies to the down-slope direction, the minus sign to the up-slope direction, while for the third case, the equations are shown as (18), and the corresponding graphic representation in Figure 3.

$$
\begin{aligned}
r_1^2 &= r_A^2 + l_1^2 + L_1^2 \\
r_2^2 &= r_A^2 + l_2^2 + L_2^2 \\
r_3^2 &= r_A^2 + l_3^2 + L_3^2 \\
\hline
r_n^2 &= r_A^2 + l_n^2 + L_n^2
\end{aligned}
\qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)
$$

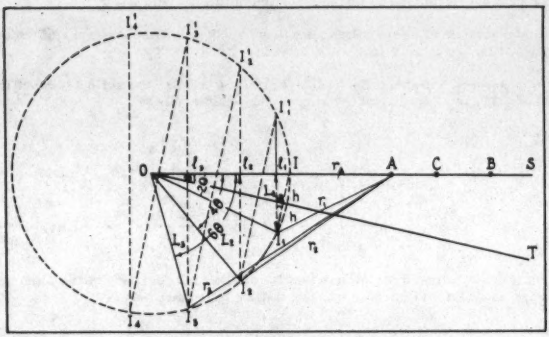

Fig. 3--Theoretical form for third case

The distances l_1, $l_2 \ldots$, L_1, L_2, can be expressed as a function of h and θ.

$$
\begin{aligned}
h &= R \sin\theta, R = \frac{h}{\sin\theta} \\
L_1 &= R \sin 2\theta = \frac{h \sin 2\theta}{\sin\theta} \\
L_2 &= R \sin 4\theta = \frac{h \sin 4\theta}{\sin\theta} \\
L_3 &= R \sin 6\theta = \frac{h \sin 6\theta}{\sin\theta} \\
\hline
L_n &= R \sin 2n\theta = \frac{h \sin 2n\theta}{\sin\theta}
\end{aligned}
\qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)
$$

$$l_1 = L_1 \tan\theta = \frac{h \sin 2\theta \tan\theta}{\sin\theta}$$

$$l_2 = L_2 \tan 2\theta = \frac{h \sin 4\theta \tan 2\theta}{\sin\theta}$$

$$l_3 = L_3 \tan 3\theta = \frac{h \sin 6\theta \tan 3\theta}{\sin\theta}$$

$$l_n = L_n \tan n\theta = \frac{h \sin 2n\theta \tan n\theta}{\sin\theta} \quad \ldots\ldots\ldots\ldots\ldots (20)$$

In consequence for the first and second cases

$$r_1^2 = \left(r_A \pm \frac{h \tan\theta \sin 2\theta}{\sin\theta}\right)^2 + \left(\frac{h \sin 2\theta}{\sin\theta}\right)^2$$

$$r_2^2 = \left(r_A \pm \frac{h \tan 2\theta \sin 4\theta}{\sin\theta}\right)^2 + \left(\frac{h \sin 4\theta}{\sin\theta}\right)^2$$

$$r_n^2 = \left(r_A \pm \frac{h \tan n\theta \sin 2n\theta}{\sin\theta}\right)^2 + \left(\frac{h \sin 2n\theta}{\sin\theta}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots (21)$$

and for the third case

$$r_1^2 = r_A^2 + \left(\frac{h \tan\theta \sin 2\theta}{\sin\theta}\right)^2 + \left(\frac{h \sin 2\theta}{\sin\theta}\right)^2$$

$$r_2^2 = r_A^2 + \left(\frac{h \tan 2\theta \sin 4\theta}{\sin\theta}\right)^2 + \left(\frac{h \sin 4\theta}{\sin\theta}\right)^2$$

$$r_n^2 = r_A^2 + \left(\frac{h \tan n\theta \sin 2n\theta}{\sin\theta}\right)^2 + \left(\frac{h \sin 2n\theta}{\sin\theta}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots (22)$$

If we call conventionally

$$\phi_n = \frac{\tan n\theta \sin 2n\theta}{\sin\theta}, \quad \frac{\sin 2n\theta}{\sin\theta} = \frac{\phi}{\tan\theta} = \phi_n \cot. n\theta$$

Then the general equations for the three cases can be written as follows

$$r_n^2 = \left(r_A \pm h\phi_n\right)^2 + \left(h\phi_n \cot n\theta\right)^2 \quad \ldots\ldots\ldots\ldots\ldots (23)$$

$$r_n^2 = r_A^2 + h^2\phi^2\left(1 + \cot^2 n\theta\right) = r_A^2 + \left(h\phi \csc. n\theta\right)^2 \quad \ldots\ldots\ldots\ldots\ldots (24)$$

We will have then for the three points A, C, and B for the two first cases, (23)

$$\begin{aligned} r_{n_A}^2 &= \left(r_A \pm h\phi\right)^2 + \left(h\phi \cot n\theta\right)^2 \\ r_{n_C}^2 &= \left(r_C \pm h\phi\right)^2 + \left(h\phi \cot n\theta\right)^2 \\ r_{n_B}^2 &= \left(r_B \pm h\phi\right)^2 + \left(h\phi \cot n\theta\right)^2 \end{aligned} \quad \ldots\ldots\ldots\ldots\ldots (25)$$

The potential for the points A, C, and B, respectively, in accordance with (16) will be

$$V_A = \frac{\rho I}{2\pi}\left(\frac{1}{r_A} + 2\sum_{n=1}^{n=\frac{\pi}{\Pi\theta}} \frac{K^n}{\sqrt{\left(r_A \pm h\phi\right)^2 + \left(h\phi \cot n\theta\right)^2}}\right) \quad \ldots\ldots\ldots\ldots\ldots (26)$$

$$V_c=\frac{\rho_1 I}{2\pi}\left(\frac{1}{r_c}+2\sum_{n=1}^{n=\frac{\pi}{2\theta}}\frac{K^n}{\sqrt{(r_c\pm h\phi)^2+(h\phi\cot n\theta)^2}}\right) \quad \ldots\ldots\ldots\ldots (27)$$

$$V_B=\frac{\rho_1 I}{2\pi}\left(\frac{1}{r_B}+2\sum_{n=1}^{n=\frac{\pi}{2\theta}}\frac{K^n}{\sqrt{(r_B\pm h\phi)^2+(h\phi\cot n\theta)^2}}\right) \quad \ldots\ldots\ldots\ldots (28)$$

The potential drops between A and C, and C and B are

$$A=\Delta V_{AC}=\frac{\rho_1 I}{2\pi}\left[\frac{r_c-r_A}{r_A r_c}+2\sum_{n=1}^{n=\frac{\pi}{2\theta}}\left(\frac{K^n}{\sqrt{(r_A\pm h\phi)^2+(h\phi\cot n\theta)^2}}-\frac{K^n}{\sqrt{(r_c\pm h\phi)^2+(h\phi\cot n\theta)^2}}\right)\right] \quad \ldots\ldots (29)$$

$$B=V_{CB}=\frac{\rho_1 I}{2\pi}\left[\frac{r_B-r_c}{r_B r_c}+2\sum_{n=1}^{n=\frac{\pi}{2\theta}}\left(\frac{K^n}{\sqrt{(r_c\pm h\phi)^2+(h\phi\cot n\theta)^2}}-\frac{K^n}{\sqrt{(r_B\pm h\phi)^2+(h\phi\cot n\theta)^2}}\right)\right] \quad \ldots\ldots (30)$$

If we combine (12), for instance, with (29), expressing the distances r_A and r_c as functions of the middle distance r, we will have the theoretical expression for the apparent resistivity allowing that $r_A = r - a/2$, $r_c = r + a/2$, and $(r_c - r_A)/r_A r_c = 1/a[(r/a)^2 - 1/4]$

$$\rho_a=\rho_1\left\{1+2\left[\left(\frac{r}{a}\right)^2-\frac{1}{4}\right]\sum_{n=1}^{n=\frac{\pi}{2\theta}}\left[\frac{K^n}{\sqrt{\left(\frac{r}{a}-\frac{1}{2}\pm\frac{h}{a}\phi\right)^2+\left(\frac{h}{a}\phi\cot n\theta\right)^2}}-\frac{K^n}{\sqrt{\left(\frac{r}{a}+\frac{1}{2}\pm\frac{h}{a}\phi\right)^2+\left(\frac{h}{a}\phi\cot n\theta\right)^2}}\right]\right\} \quad \ldots (31)$$

As the ratio R = r/a can be fixed, we can express as a function of it the relation h/a = Rh/r, so that (31) can be written as follows:

$$\rho_a=\rho_1\left\{1+2\left[\left(\frac{r}{a}\right)^2-\frac{1}{4}\right]\sum_{n=1}^{n=\frac{\pi}{2\theta}}\left[\frac{K^n}{\sqrt{\left[R\left(1\pm\frac{h}{r}\phi\right)-\frac{1}{2}\right]^2+\left(\frac{Rh}{r}\phi\cot n\phi\right)^2}}-\frac{K^n}{\sqrt{\left[R\left(1\pm\frac{h}{r}\phi\right)+\frac{1}{2}\right]^2+\left(\frac{Rh}{r}\phi\cot n\phi\right)^2}}\right]\right\} \quad \ldots\ldots (32)$$

In (32), once the value of R is fixed, as the reflection coefficient varies from + 1 to - 1, values can be given to the relative penetration h/r for computing families of interpretation graphics, varying θ, in steps of 10°, for example.

In the same manner we would find that the potential drops between A and C, and C and B for the third case are

$$A=\Delta V_{AC}=\frac{\rho_1 I}{2\pi}\left[\frac{r_c-r_A}{r_A r_c}+2\sum_{n=1}^{n=\frac{\pi}{2\theta}}\left(\frac{K^n}{\sqrt{r_A^2+(h\phi\csc n\theta)^2}}-\frac{K^n}{\sqrt{r_c^2+(h\phi\csc n\theta)^2}}\right)\right] \quad \ldots\ldots\ldots (33)$$

$$B=\Delta V_{CB}=\frac{\rho_1 I}{2\pi}\left[\frac{r_B-r_c}{r_B r_c}+2\sum_{n=1}^{n=\frac{\pi}{2\theta}}\left(\frac{K^n}{\sqrt{r_c^2+(h\phi\,tg\,n\theta)^2}}-\frac{K^n}{\sqrt{r_B^2+(h\phi\,tg\,n\theta)^2}}\right)\right] \quad \ldots\ldots\ldots (34)$$

And combining (12) with (33) we will have the equation for the apparent resistivity

$$\rho_a=\rho_1\left\{1+2\left[\left(\frac{r}{a}\right)^2-\frac{1}{4}\right]\sum_{n=1}^{n=\frac{\pi}{2\theta}}\left[\frac{K^n}{\sqrt{\left(\frac{r}{a}-\frac{1}{2}\right)^2+\left(\frac{h}{a}\phi\,tg\,n\theta\right)^2}}-\frac{K^n}{\sqrt{\left(\frac{r}{a}+\frac{1}{2}\right)^2+\left(\frac{h}{a}\phi\,tg\,n\theta\right)^2}}\right]\right\} \quad \ldots\ldots (35)$$

or

$$\rho_A = \rho_1 \left\{ 1 + 2\left(R^2 \frac{1}{4}\right) \sum_{n=1}^{n=\frac{1}{10}} \left[\frac{K^n}{\sqrt{\left(R-\frac{1}{2}\right)^2 + \left(\frac{Rh}{r}\phi \operatorname{tg} n\theta\right)^2}} - \frac{K^n}{\sqrt{\left(R+\frac{1}{2}\right)^2 + \left(\frac{Rh}{r}\phi \operatorname{tg} n\theta\right)^2}} \right] \right\} \quad \ldots\ldots\ldots (36)$$

As we have determined the equations of the apparent resistivity for the three cases considered, we will pass on to compute the values of the relations of the potential drops also for the three analyzed cases.

Dividing (29) by (30) for the first and second cases, we have

$$\frac{A}{B} = \frac{\frac{(r_c - r_A)h}{r_A r_c} + 2\sum_{n=1}^{n=\frac{1}{10}} \left[\frac{K^n}{\sqrt{\left(\frac{r_A}{h} \pm \phi\right)^2 \pm \left(\phi \cot n\theta\right)^2}} - \frac{K^n}{\sqrt{\left(\frac{r_A}{h} \pm \phi\right)^2 + \left(\phi \cot n\theta\right)^2}} \right]}{\frac{(r_B - r_c)h}{r_B r_c} + 2\sum_{n=1}^{n=\frac{1}{10}} \left[\frac{K^n}{\sqrt{\left(\frac{r_A}{h} \pm \phi\right)^2 \pm \left(\phi \cot n\theta\right)^2}} - \frac{K^n}{\sqrt{\left(\frac{r_A}{h} \pm \phi\right)^2 + \left(\phi \cot n\theta\right)^2}} \right]} \quad \ldots\ldots\ldots (37)$$

In the same way dividing (33) by (34) we obtain the equation for the third case.

$$\frac{A}{B} = \frac{\frac{(r_c - r_A)h}{r_A r_c} + 2\sum_{n=1}^{n=\frac{1}{10}} \left[\frac{K^n}{\sqrt{\left(\frac{r_A}{h}\right)^2 + \left(\phi \operatorname{tg} n\theta\right)^2}} - \frac{K^n}{\sqrt{\left(\frac{r_c}{h}\right)^2 + \left(\phi \operatorname{tg} n\theta\right)^2}} \right]}{\frac{(r_B - r_c)h}{r_B r_c} + 2\sum_{n=1}^{n=\frac{1}{10}} \left[\frac{K^n}{\sqrt{\left(\frac{r_A}{h}\right)^2 + \left(\phi \operatorname{tg} n\theta\right)^2}} - \frac{K^n}{\sqrt{\left(\frac{r_B}{h}\right)^2 + \left(\phi \operatorname{tg} n\theta\right)^2}} \right]} \quad \ldots\ldots\ldots (38)$$

Equations (37) and (38) are general and from them we will start to apply any of the three alternates of the method. Actually only the author's modality interests us for which we will eliminate the distances r_A and r_B expressing them as functions of r_c, in order that the relations remain referred to the central distance, having in mind that according to (3), (5), and (6)

$$r_A = r_C\,(R - 0.5)/(R + 0.5) = r_c/F \text{ and } r_B = r_C\,(R + 0.5)/(R - 0.5) = Fr_C$$

F is the normal ratio (see Equ. 10). Equations (37) and (38) will remain definitively as follows if $x = r_c/h$

$$\frac{A}{B} = \frac{\frac{F-1}{x} + 2\sum_{n=1}^{n=\frac{1}{10}} \left[\frac{K^n}{\sqrt{\left(\frac{x}{F} \pm \phi\right)^2 + \left(\phi \cot n\theta\right)^2}} - \frac{K^n}{\sqrt{\left(x \pm \phi\right)^2 + \left(\phi \cot n\theta\right)^2}} \right]}{\frac{F-1}{xF} + 2\sum_{n=1}^{n=\frac{1}{10}} \left[\frac{K^n}{\sqrt{\left(x \pm \phi\right)^2 + \left(\phi \cot n\theta\right)^2}} - \frac{K^n}{\sqrt{\left(Fx \pm \phi\right)^2 + \left(\phi \cot n\theta\right)^2}} \right]} \quad \ldots\ldots\ldots (39)$$

$$\frac{A}{B} = \frac{\frac{F-1}{x} + 2\sum_{n=1}^{n=\frac{1}{10}} \left[\frac{K^n}{\sqrt{\left(\frac{x}{F}\right)^2 + \left(\phi \operatorname{tg} n\theta\right)^2}} - \frac{K^n}{\sqrt{x^2 + \left(\phi \operatorname{tg} n\theta\right)^2}} \right]}{\frac{F-1}{xF} + 2\sum_{n=1}^{n=\frac{1}{10}} \left[\frac{K^n}{\sqrt{x^2 + \left(\phi \operatorname{tg} n\theta\right)^2}} - \frac{K^n}{\sqrt{\left(Fx\right)^2 + \left(\phi \operatorname{tg} n\theta\right)^2}} \right]} \quad \ldots\ldots\ldots (40)$$

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GERMAN OCEANOGRAPHIC WORK, 1934-1945

Gunther Boehnecke and Collaborators

(Condensed by John Lyman)

Foreword--This review was prepared by G. Boehnecke, with the assistance of other German oceanographers, for James N. Carruthers, Oceanographer to the Hydrographic Department of the British Admiralty, while the latter (serving as Commander in the Special Branch of the RNVR) was investigating German oceanography after the Surrender. A copy (in the original German) was tabled at the Stockholm Meeting of the International Council for the Exploration of the Sea, August 1946. The present version has been condensed from an English translation, the German original being unavailable, and a bibliography has been added from material available in the files of the United States Navy Hydrographic Office. It is emphasized that the bibliography is not intended to be comprehensive, but an effort has been made to draw attention to matter in the discussion that has already been published. References followed by one- or two-digit numbers, instead of years, refer to unpublished scientific reports, listed on p. 136 of this issue of the Transactions.

Introduction--German oceanographic work was greatly expanded in the last two years before World War II, and even more during the War. Personnel, equipment (ships, aircraft, and instruments), and funds were all augmented. This was primarily for obtaining the answers to practical questions, but since the questions depended largely on the solution to theoretical problems, German scientists availed themselves of the rich opportunities for compiling material, and systematically used them in such a manner that whenever possible they took data which could be used for advancing general oceanographic knowledge in time of peace to come, but which had no immediate bearing on the problem in hand. Although evaluation of these observations could not be carried out under war conditions, most of the material escaped destruction, and is now being worked up in the new German Hydrographic Institute, which was formed under Allied control from the Deutsche Seewarte and the Marine Observatory.

The most important investigations--In the years immediately before the War, the most important German expeditions were two Atlantic cruises by the Meteor in 1937 and 1938, a voyage by the Meteor to the Irminger and Norwegian Seas in 1935, and the Gulf Stream survey by the Altair in 1938. The Antarctic was visited by the Schwabenland and Jan Wellem, and a number of investigations in the North Sea and Baltic were carried on by the Poseidon, Triton, and other vessels.

All international cooperation ceased at the outbreak of the War, and German oceanographers were handed a series of urgent practical problems. Two or three years were required before these problems were advanced to the state where they needed investigation at sea. Thus not until 1942 were the cruises of the Gauss begun in Putziger Bay for under-water sound investigations, while work by the Börgen, Triton, Gauss, and other vessels on the microstructure of the upper layers of the sea began in the German Bight in 1941. In the later part of the War, such studies were extended to the coasts of the occupied countries.

Structure of the ocean--Since 1934, German ships, in addition to making several thousand surface temperature observations, have occupied 1500 oceanographic stations and obtained nearly 3700 serial observations. The annual total of the latter increased rapidly from 1934 until 1938, when 1254 observations were made; it was under 60 for each of the next three War years, but increased to almost 500 in 1942 and remained near that level in 1943 and 1944.

These observations were chiefly used for preparation of the Atlas der Dichte des Meerwassers, 12 sections of which were issued by the Oberkommando der Kriegsmarine during the War, showing density distribution at the surface, and at 10, 30, 60, and 100 m. The material was also used in compiling manuals and sailing directions, including those for submarines. Foreign observations were also employed, as in the Handbuch für das Schwarze Meer, 1943.

The thermohaline structure of the ocean is not only of essential importance for characterizing and differentiating the water masses, but also is of even greater significance in connection with study of the motional processes in the sea. Thus DEFANT [see "References" at end of paper, 1938] derived the water movements in the Atlantic from the localization of the various recognizable layers. He was able to arrive at the position of the zone of no motion and thereby deduce absolute current velocities. Publications by DIETRICH [1936] and HANSEN [1936] discuss similar problems.

Recent investigations called attention to the fact that above the thermocline, individual observations may yield misleading values, caused by internal waves, inertial oscillations, and horizontal and vertical turbulence. KALLE [1942] discussed such temperature variations and NEUMANN [see special list in "Bibliography, Oceanography," p. 136, 17] theoretically derived internal wave periods.

Kinematics and dynamics--Observations in this field included current and sea level measurements. High-sea and coastal gages recorded the latter, while current observations were made both by expedition vessels and by German lightships. There are available 219,000 two-hourly surface current observations from the light vessels. Continuous records were made with Boehnecke and Rauschelbach current meters at standard depths from anchored ships, and with "paddlewheel meters," which were planted unattended for fortnightly periods. Most of the observations were fairly shallow, but a few Meteor stations went down to 800 m.

During the War special expeditions were sent out to measure currents along occupied coasts, and the number of anchor stations by the Börgen and Triton along the Norwegian coast exceeds 35 per one degree quadrangle in several places. A total of 2561 days of observation in over 1400 locations is available for the ten-year period, equivalent to the full time of one vessel for over seven years.

Current observations from 40,000 ships' logs in the archives of the Deutsche Seewarte were entered on 900,000 Hollerith punch cards, which, however, were lost by fire in the course of the War. The results had been tabulated, and SCHUMACHER [1940 and 1943] used them for constructing current charts. As shown in Figure 1, the later editions of these charts give not only the predominating direction and mean drift, for the use of the mariner, but also current roses for the benefit of the specialist. Between 1940 and 1944 the Seewarte published a series of Monatskarten des Nord und Südatlantischen Ozeans, using the largest number of ship observations yet available for such a work. SCHOTT [1942] published a world chart of currents as a German Admiralty chart.

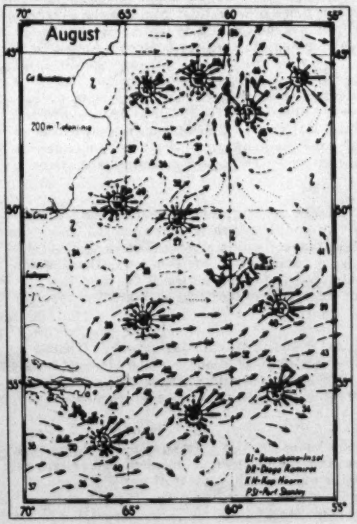

Fig. 1--Data on ocean currents in August

A synoptic oceanographic observation system was also developed, used chiefly in connection with ice predictions, which reached final development in the form shown in Figure 2. In addition to hourly water levels from 22 gage stations, hourly current data and temperatures from surface to bottom from lightships and the guard ships anchored in the Belt, and harbor water temperatures, the system used observations from the Gauss, which was ordered from Hamburg to the indicated location of the front between the North Sea and Baltic water.

More than 50 publications on water level and currents were issued in Germany in the last ten years, by such authors as W. Hansen, F. Model, G. Neumann, and H. Thorade (who died of leukemia in May 1945). HANSEN [5] generalized the methods which Sterneck and Defant had developed for ascertaining the oscillations in a one-dimensionally extended channel, and derived means for determining vertical and horizontal movements of completely or partially closed bodies of water, using only observations along the coast and at the boundary with the adjacent ocean. It is hoped that this method can be extended to the problem of oceanic

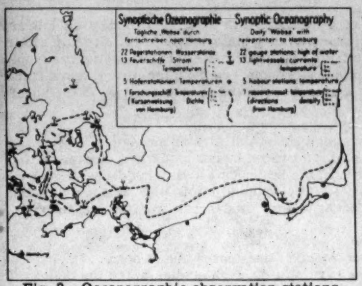

Fig. 2--Oceanographic observation stations

tides, which so far have defied mathematical treatment. Certain preliminary studies have already been made in this field, particularly concerning the disturbing influence of islands on oceanic tides. THORADE [1943] considered the behavior of a tidal wave running up a shelf, and the resulting methods, supported by observations, were used in preparing atlases of harmonic constants.

A thorough study was made by HANSEN [1942] of the influence of friction on currents. The laws of flow for pipes and flumes were found applicable also to rivers and oceans, and distribution of velocity from surface to bottom could be determined by using a general coefficient of friction varying appropriately with depth. The distribution of velocity in density currents and in tidal currents obeyed identical laws. A further result was an explanation of the origin of turbulence in a water stream. The profile of velocity was stable only if the kinematic viscosity was high.

The dynamic theory of currents was tested by measurements in the Skagerrak on a profile from the Skaw to Arendal. Simultaneous temperature-salinity and "paddle-wheel meter" observations were taken, and by choosing a suitable level of zero motion, a satisfactory agreement between computed and observed current was obtained.

Incidental to other observations, model trials were made at sea of the behavior of floating bodies in strong currents and high seas. The Little Belt proved particularly suitable for such work, observations being made from the high bridge there. Studies of short-period pressure variations on the bottom showed that even during high seas the ordinary short waves of the Little Belt did not affect the bottom pressure at ten to twenty m.

SCHUMACHER [1939] further elaborated the stereophotogrammetric method of studying waves. Stereo-movies were taken on the Europa in 1938-1939 at one frame per sec. From the photographs, 30 contoured charts of wave forms were published. The largest waves observed from Europa were 15 to 16 m high, with length 300 m. Observed length height ratios ranged from 17.6 to 92.2, although theory called for values as low as seven. Diagrams were prepared showing the relationship between wind force and wave height, length, period, and velocity for the North Sea, Baltic, Central Atlantic, and North Atlantic.

Marine optics--Using in part some novel instruments, various investigations in this field were undertaken during the War, in determining color, transparency, turbidity, and light-absorption in the sea. Special attention was always given to the connection between optical phenomena and other oceanographic properties, and a number of new relationships were discovered thereby.

KALLE [1938] designed a color-measuring instrument by which any observed color could be resolved as a combination of five basic components. The blue of extremely pure ocean water, as in the Sargasso Sea, was determined as equivalent to the color of wave length 477 μ. The Baltic was found to contain both yellow and fluorescent substances [KALLE, 28]. Measurements were also made of the polarization of light in the transparent waters of the Sargasso Sea.

Kalle also constructed a turbidity meter for quantitative measurements in the Central Atlantic, which could determine turbidity down to one K (coefficient of extinction 4×10^{-5}/cm) on a 50 ml sample. The average surface turbidity of the Sargasso Sea was found to be 2.5 to five K, contrasted with 50 K in the Baltic and 100 K in the North Sea. Deeper water in the Atlantic was even clearer than the surface, except for scattered water masses in the deep Atlantic, where values of 50 to over 100 K were encountered. These are attributed to submarine volcanic activities.

WATTENBERG [1938a] measured the transparency of sea water and the penetration of sunlight using the usual photo-cells. The results in Norwegian waters are of particular interest, contrasting the clear water of high salinity at the entrance to fjords with the turbid surface water of low salinity inside.

Joseph and Wattenberg made comprehensive investigations in marine optics, beginning in 1942. Among new instruments devised for the purpose are a three-cell photometer, which can measure

transmitted light in three spectral bands at once, or be connected in parallel with identical filters for measurements in bands having high extinction; transparency meters with six filters adjustable by remote control, with an optical system shielded from the disturbing effects of daylight; a transparency meter with high-voltage mercury lamp, for measurements in the ultra-violet; and a transparency meter mounted in a paravane, providing a continuous record of transparency in the upper layers during a voyage.

Numerous measurements were made with these instruments in various sea areas. Particular mention should be made of the turbidity strata, probably plankton layers only a few centimeters thick, which settle down in the Belts and in the Sound at the interface between the dense, high-salinity water of the North Sea, and the lighter, low-salinity water of the Baltic. The investigation of their temporary vertical variations offers a valuable tool for studying internal waves, turbulence, water exchange and other factors.

Simultaneous measurements of vertical and horizontal transparency are of special importance in areas where water masses of different character have mixed. Such studies in the North Sea off Limfjord show the influence of the tidal stream on the conditions of turbidity.

A theoretical investigation by JOSEPH [40] of the extinction of light in the sea showed that a distinction must be made between light scattered forward and light scattered backward, thoroughly discussed the accuracy of methods for measuring extinction, and interpreted the results obtained.

It was found that the transparency of sea water in the ultra-violet was as suitable a means of characterizing a water mass as its salinity. Kalle traced the characteristic yellow Baltic water well out into the Atlantic. The fact that measurements are obtained in situ and are simple to compute is suggested as advantageous.

Joseph also derived a theory for interpreting Secchi disk values, which resulted in the recommendation that readings be taken with both white and black disks. The difference between the two numbers has a more distinct relationship to the coefficient of extinction than readings of one disk only, and personal factors are largely eliminated.

Underwater sound--Development of instruments for transmitting and receiving sound under water was largely confined to the problems of sound ranging and signal transmission in a horizontal direction in the upper layers. It was very soon discovered that the conditions here were much more complicated than in the vertical paths used in sonic sounding, and it became necessary to examine the structure of the upper water layers.

Ten years' work by H. Thorade and K. Kalle showed first of all that the speed of sound was chiefly dependent on water temperature, and that the distribution of density had little to do with the distribution of sound speed. A nomogram [KALLE, 1941] was constructed for converting observed temperature and salinity into sound speed. Next, the relation between the speed of sound and its refraction, already determined by Monn, was rediscovered, and from this the path of a sound ray in the sea under known conditions of sound speed could be computed. Next came the devising of means to compute ray paths directly from serial oceanographic observations, first a set of elliptical "sound-stencils," next a nomogram christened the "peacock's tail," and finally an "acoustic slide rule."

Now came the sea test of the theory. Expeditions were sent to the coast of Norway, the Danzig Bight, and the Bornholm Basin. The expected relationships between the oceanographic conditions and the propagation of sound were in general confirmed; but the problem was still found to be more intricate than could be explained by the ordinary oceanographic observations.

The Deutsche Seewarte therefore sought a more sensitive instrument than the usual water bottle with mercury thermometer. K. Kalle developed the thermo-electric "streak-meter," which, working with a minimum of lag, led to the discovery of a phenomenon designated the "internal thermal commotion of the ocean" [KALLE, 1942]. As a further refinement, the Marine Observatory devised the "gradient-meter," by which it was possible to determine directly the temperature gradient in a water column and which improved the understanding of the thermal stratification of water masses. From these results the conclusion was drawn that the ocean is to be looked upon as an acoustically turbid, rather than an acoustically clear, medium.

Chemistry of sea water--Work under this heading concerned analytical procedures, regional investigations, and theoretical and practical problems arising from such investigations.

K. Kalle proposed indol-sulfuric acid instead of the Griess-Ilosvay reagent for the determination of nitrite, since it is less sensitive to interfering reactions such as occur in coastal waters.

WATTENBERG and WITTIG [1938] worked on the determination of titratable base, and succeeded in reducing the quantity of sea water required for the titration from 200 ml to 50 or 100 ml, also simplifying the procedure. GOEDECKE [1939] emphasized the necessity of filtering the water before this analysis. KALLE [1939] correspondingly improved the determination of dissolved oxygen, and constructed a nomogram for saturation values in terms of salinity and temperature. MEYER [1938] of the Institute at Kiel applied the Pulfrich photometer to the determination of traces of copper in sea water.

The chief regional investigation was that of the Meteor in the North Atlantic in 1937 and 1938, but the results so far have had only preliminary study. H. Wattenberg participated in the expedition from February to May 1937, and K. Kalle from January to May 1938. Areas of special interest were the upwelling zones off the northwest coast of Africa, and the Sargasso Sea. In the former region, WATTENBERG [1938b] was able to demonstrate the existence of a pronounced phosphate maximum more than 100 m below the oxygen minimum layer, and a secondary silicate maximum a corresponding distance below the phosphate maximum. KALLE [1939b] confirmed this observation the following season in the central Atlantic. Minima were found near the bottom and in areas of turbidity, presumably caused by adsorption on the particulate matter.

Other regional studies were those of nutrients and titratable base by KALLE [1937] and GOEDECKE [1937], which demonstrated that the detailed picture of the structure of the sea is improved by adding various chemical determinations to the ordinary characterization of water masses by temperature-salinity relationships. Similar work by WATTENBERG [1939a and 1941] in the Baltic showed the phosphate-silicate ratio to be of special interest there. KALLE [1943a] found a periodic rhythym in the cycle of regeneration of the deep water of the Baltic, using the recorded observations since 1926 from the Gotland Deep.

The researches of WITTIG [1940] at the Kiel Institute on the calcium content of the Baltic and the yearly cycle of nutrients in the Kieler Bucht demonstrated the peculiar position of the Baltic compared with other sea areas. LUENEBURG [1939] of the Deutsche Seewarte conducted a similar investigation of the Elbe estuary in connection with the question of the water exchange between the Elbe and the German Bight, following by several years a study of the calcium distribution of the same area by GOEDECKE [1936].

Wattenberg and collaborators prepared three reports on the calcium cycle in the sea. The first [WATTENBERG, 1935] discussed the possibility of deriving current velocities in deep water from the distribution of calcium, and arrived at a mean velocity of one-half to one cm/sec for the Antarctic bottom current. The other two [WATTENBERG and TIMMERMANN, 1936, 1938] dealt with experimental determination of the solubility product of calcium, magnesium, and strontium carbonates in sea water. In further works, WATTENBERG [1939b and 1943] reviewed the problem of the oxygen minimum in the sea and the general behavior of dissolved gases at great depths. He was killed in an air raid in 1944.

In conclusion, mention should be made of KALLE [1943b], who summarized existing knowledge of chemical cycles in the sea.

Morphology--German research workers participated in obtaining oceanic soundings, preparing bathymetric charts, and interpreting the bottom relief. In addition to hydrographic surveys in home waters, soundings were obtained by most German oceanographic expeditions, in particular by the Meteor and Altair in the North Atlantic in 1934-1939. During the War, a systematic survey, including collection of bottom samples, was made of the fjord sills along the Norwegian coast, but the results have not yet been published.

The Atlantic surveys, on the other hand, have been published in a series of comprehensive bathymetric charts. The chart of the Atlantic brought out in 1934 by Th. Stocks in the Meteor Reports has been refined by several 1:250,000 charts of the Reykjanes Ridge, part of the Mid-Atlantic Ridge north of the Azores, and the Azores Plateau itself. STOCKS [1939, 1941] has also issued the first four sheets, covering most of the South Atlantic, of a projected 1:5-million chart of the Atlantic.

The detailed topographic picture thus obtained lends itself to morphological examinations. DIETRICH [1939] and G. Wuest proved that, in almost every case where sufficient information is available, the Mid-Atlantic Ridge does not form a single lengthy dam, but consists of three to nine

parallel sharply-cut detached ridges, separated from each other by deep grooves. Parts of the branches from the main ridge, particularly the Azores Plateau, show a similar structure. The mean distance between these detached ridges is 20 to 30 km, and many of them are 3000 m higher than the intervening grooves, with mean slopes of 10 to 20 degrees and maxima up to 34 degrees. Elevations with alpine relief of this kind form a sharp contrast to the almost plane sea floor from which they emerge.

The next question is as to how these forms arose. Using the detailed description by WUEST [1939] CLOOS [1939] postulated that the Azores Plateau is not a fold structure, but resulted from tectonic fractures which formed fissures. Magma emerging from these fissures piled up in the longitudinal ridges. Cloos found similar structures in other parts of the ocean, in the Gulf of Aden, for example. It appears that the gross relief in mid-ocean is not the result of folding, as is the case with most continental mountain chains, but of tectonic fissuring and volcanic deposition.

The steepest angles of elevation yet observed in connection with such deposits was ascertained by Defant and Wuest as 52°.5.

Geology--During the War a marine geological department was established at the Deutsche Seewarte, for the purpose of correcting the bottom indications on charts. A central collection of bottom samples was created, using material collected previously in the North Sea and Baltic, samples obtained from the Navy and merchant ships of mud that came up with ships' anchors, and the results of special exploring voyages sent out for the purpose. Thus more than 1000 samples were obtained from the southern part of the middle Baltic, and over 300 from a strip across the North Sea to the Dogger Bank. This collection has survived the War.

O. Pratje, studying the functioning of coring tubes, found that in many cases the cores were incomplete and directed his efforts toward improving samplers. A Piggot gun was tested in the Baltic, and efforts made toward obtaining similar long cores without using powder charges. Finally a new type of sampler was devised, which unfortunately was seriously damaged by an air raid.

The preliminary results of the collection of bottom samples were published in the Atlas der Bodenbeschaffenheit des Meeres, of which 13 sections were issued. In preparing these, Pratje considered the sediments from the point of view of their hydrographic environment. Thus the coarseness of sediments depends on the maximum tidal current, and conclusions may be drawn from the graining and the current as to the movement of the sand. Conversely, water containing sand in suspension has a greater density than water free of sand.

Other reports of work in marine geology appeared in the publications of the Senckenberg Museum at Frankfort-am-Main, and in the journal Geologie der Meere und Binnengewässer.

Oceanographic instruments--Existing instruments were used to a considerable extent in accomplishing the work described herein. BOEHNECKE [1937] and RAUSCHELBACH [1929] current meters, Nansen bottles, Pettersson insulated bottles, and sets of hydrometers were employed. The latter were used only when it was impractical to preserve water samples in bottles. Long period vertical movements were measured by the RAUSCHELBACH [1932] high-sea gage; short period movements by the Schumacher stereophotogrammetric method. Topography and geology were studied with Atlas and Elektroakustik echo sounders, Van Veen and Pettersson dredges and grabs, coring tubes, and sand traps.

For other specific tasks, new instruments were developed. Among these were a current meter by RENNER [25], an instrument for measuring temperature and salinity in situ [WATTENBERG and JOSEPH, 1943], and a semi-automatic potentiometric titration, also by Joseph and Wattenberg; a device for tele-transmission and automatic telephonic transmission of gage values, christened the "talking gage;" various developments of the Rauschelbach high-sea gage [TOMCZAK, 20]; and several other instruments for measuring long- and short-period pressure variations, using either Bourdon tubes or a new electromagnetic principle.

Three other new instruments can be described in more detail. The first is the so-called "paddlewheel current meter," which can be anchored at the bottom of the sea and will function automatically for a period up to four weeks. The recording of rotations of the 50 cm diameter paddlewheel and directions of the compass card is done photographically, 100 feet of film sufficing for four weeks. The instrument can be planted in water up to 50 m depth, and by adding a pressure gage, a versatile combined sea-level meter and current recorder results.

Wattenberg and Joseph devised a conductimetric shipboard salinity determination based on simultaneous comparison of the sample and a standard water of known salinity at the same temperature in a thermostat, using an alternating-current bridge. Adjustment of the resistances using an audible signal proved feasible even near the engine room; but visual indication could also be used. The accuracy of this method is claimed as at least equal to that of titration.

The third instrument is a "sea-motion gage" developed by Joseph and Tomczak. By eliminating the damping in the Rauschelbach gage, the instrument becomes sensitive to the short-period pressure variations caused by sea and swell. These motions of the water level are recorded photographically by placing a slit and light source behind the measuring tube and leading sensitized paper past it. Enough paper is provided for one hour's record. Since the apparatus cannot be handled in a rough sea, it must be set before the sea gets up. A starting mechanism was devised which automatically turned on the gage as soon as a predetermined wave amplitude occurred, and turned it off when the hour was up. A special clockwork indicated day and hour of functioning. This starting mechanism, called the "gradient interpolation apparatus" was designed as an independent unit, capable of submersion to 20 m, and suitable for controlling any oceanographic instrument which one does not wish to operate until pressure variations reach a certain value.

Ice--Both ice research and the ice-reporting service were extended during the War. An international ice-reporting service was established in 1903, and the German Ice Service maintained ice observations in the occupied countries, even including the Black Sea in 1941-1943. Because of the severity of the first three winters of the War, ice observations were made by aircraft, in addition to those made along shore, and as a result the ideas concerning the freezing of the southern Baltic were completely changed. It had been assumed, before the War, that in severe winters the coastal ice area widened, but the central part of the sea remained unfrozen; however, the observation flights showed that the whole Baltic becomes ice-covered. This state of affairs prevailed, for example, from February 5 to March 27, 1942.

Ice observations by aircraft were extended to the North Sea and Atlantic in 1942, and were augmented by observations from submarines, as shown in Figure 3. Never before had most of

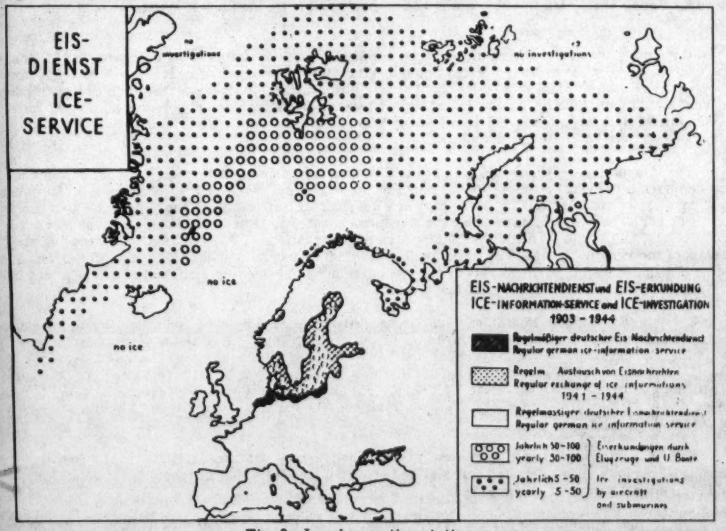

Fig. 3--Ice observation stations

this area been made the object of so intense an ice-exploration, and together with the results of other belligerent nations, these observations should result in a much more nearly accurate

description of ice conditions in the Arctic Atlantic. The Ice Service also prepared and published atlases of Monatskarten des Nordatlantischen Ozeans and Uebersichtskarten der Eisverhältnisse im gesamten Nordpolargebiet. Several unpublished investigations by J. Büdel on the geography of sea ice exist; they show that characteristic climatic ice regions recur in various parts of the world.

A synoptic ice service was also organized during the War. With daily ice charts of the North, Baltic, and Black Seas available, weekly charts of the Polar Sea, the weather map, and the synoptic oceanographic chart of the sea area in question, it issued regular ice predictions. For the southern Baltic, both short range (1- to 3-day) and long range (5- to 10-day) forecasts were issued, beginning in 1942-1943, which proved 80 per cent accurate.

Tides--Tidal studies in Germany during the last decade, beside those already described under kinematics and dynamics, were concerned with (1) preparing and issuing tide tables, atlases, and other aids to mariners, (2) development of methods for prediction of tides and calculation of tidal constants, (3) observations of tides and determination of harmonic and nonharmonic constants, and (4) storm-tide warning service for the coasts and estuaries of the German Bight. The events and demands of war hindered the second item, but unexpectedly extended the third.

Under the first heading come the familiar Gezeitentafeln of the Marine Observatory, and atlases of tidal streams in European waters. A compact ten-component tide-predictor (20 × 30 × 60 cm) was developed for shipboard use, originally for merchant ships running to Asia, but restricted during the War to naval vessels. A similar predictor was also developed for computing direction and speed of a tidal stream from the harmonic constants of its North and East components.

Prediction of tides for German ports is difficult because of the shallow water of the German Bight. An extensive nonharmonic analysis is being undertaken, including investigation of the aperiodic changes found in all German ports, which, since they show many common features, cannot entirely be attributed to the effects of channel regulation. Harmonic analysis was found to require consideration of 60 to 65 astronomic and shallow-water constituents, exceeding the capacity of the existing tide-predicting machines. A 62-component machine, the largest in the world, was therefore completed in 1938, which can compute and print high and low waters for a year in 20 hours.

Determination of the values of the large number of tidal constants to be used with the 62-component machine by the ordinary method of approximations proved unsatisfactory, and an analyser was designed which would reduce the 9000 hourly observations of a year, entered on Hollerith punch cards, to 125 equations by the method of least squares. The machine, 80 per cent complete, was dismantled for safety in the final years of the War, and is now lost. The 125 equations were to have been solved by Hollerith machines.

The International Hydrographic Bureau at Monaco keeps up-to-date a special publication containing harmonic tidal constants for all ports of the world, but there is great variation in the method and duration of observations by which they are derived. During the War, therefore, German mechanical tide gages were maintained along the European coast from Norway to Spain, Spanish Morocco, and Greece, and produced a total of 50,267 days of observations at 260 stations. An intensive analysis of the results is underway, which will yield tidal constants and data for some 50 German and other European ports. A large part of the computation has been completed, and it is hoped that the results will be published in the next few years.

Tides on the German North Sea coast are greatly influenced by wind and atmospheric pressure, because of the shape and northwest exposure of the German Bight. Low water level only hinders shipping, but unusual rises damage dikes and harbor works, and cause heavy losses of livestock along the shores. A telegraph warning-service was developed; but a real forecasting service was required, and by the outbreak of the War numerical forecasts of high water level were being issued twice daily, within an accuracy of 0.2 m, while storm tide warnings were given 12 hours or more in advance.

Future investigations will be concentrated on the frequent nontidal oscillations of a longer-than-tidal periods, more detailed correlation between water level and meteorological conditions, and the general nature of storm surges.

Conclusion--It should be particularly emphasized that German observers availed themselves of the extraordinarily abundant possibilities of collecting data during the War, and compiled them systematically with a view to full utilization in times of peace. This material is now awaiting scientific elaboration.

APPENDIX--1

List of vessels engaged in oceanographic investigations for the Deutsche Seewarte or Marine Observatory, or working in cooperation with one of those institutions, 1934-1945. (Dimensions given are length and beam in feet; tonnages gross register).

Ahne, yard tug, 102 × 21; 1929-1938, studies of compass-needle deviation in current meters; current measurement and hydrographic work in German Bight.

Altair, coal burner, reciprocating engine, 325 × 46, 2414 tons; 1938, International Exploration of the Gulf Stream.

Börgen, coal burner, reciprocating engine, 184 × 30, 941 tons, cruising range 3800 miles at eight knots; 1940-1945, hydrographic work, current measurement, instruction, and other work, in Norwegian waters, North Sea, and Baltic.

Gauss, coal burner, reciprocating engine, 180 × 28, 745 tons, 7 knots; 1941-1945, degaussing, oceanographic, and magnetic work, and instruction, in Skagerrak, Kattegat, and Baltic.

Geeste, Naval tug; July-August 1934, and June-July 1937, current measurement and hydrographic work in German Bight and on Dogger Bank.

Hecht, fleet tender, coal burner, reciprocating engine, 216 × 33, 999 tons, 9 knots; June-September 1937, current measurements and hydrographic work in German Bight.

Jan Wellem, whale factory, oil burner, reciprocating engine, 465 × 72, 11,776 tons; 1937-1939, oceanographic and meteorological observations in Antarctic.

Kjerstadtinn, Norwegian fishing cutter; 1942-1944, summer current measurement and hydrographic work in German Bight.

Lauting, motor lighter; May-June 1945, current measurements and hydrographic work in German Bight.

Mellum, motor lighthouse tender; 1934-1940, mooring and testing gear in German Bight and North Sea, in addition to buoy work.

Meteor, motorship, 233 × 33, 1167 tons, cruising range 6000 miles at 14 knots; 1935, spring and autumn, current measurements and oceanographic investigations, Iceland and Greenland waters; 1935, autumn, in Norwegian waters; 1936, spring and autumn, testing gear in Norwegian waters; 1937 and 1938, spring, German North Atlantic Expedition.

Poseidon, State exploring vessel, coal burner, reciprocating engine, 150 × 30, 453 tons; until 1940, hydrographic and biological research in Baltic, North Sea, and Barents Sea.

Rungholt, twin-screw tug, coal burner, 8 1/2 knots, surveying vessel of the Prussian Marsh Reclamation Authority; May 1939-April 1945, current measurement and hydrographic work in Danish waters, North Sea, and Baltic.

Schwabenland, motorship, 468 × 60, 8631 tons; 1938-1939, German Antarctic Expedition.

Teutoburger Wald, weather ship, trawler type, coal burner, reciprocating engine, 180 × 30, 550 tons, 12 1/2 knots; December 1944-February 1945, testing instruments in Little Belt, hydrographic work and current measurements in Skagerrak and Kattegat.

Triton (ex-Forelle), oil burner, reciprocating engine, 220 × 33, 1205 tons, crusing radius 8000 miles at 11 1/2 knots; 1939, summer hydrographic and chemical work in the Baltic; 1942-1944, instruction, current measurements, oceanographic, and hydrographic work in Baltic and Danish and Norwegian waters; lost 1944.

Triton, lighthouse tender; 1934-1939, mooring and testing instruments in German Bight and North Sea, in addition to regular buoy work.

Wik, lighthouse tender; 1934-1939, mooring and testing deep-water gages and paddlewheel current meters in German Bight and North Sea, in addition to regular buoy-tending.

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ACTIVITY OF PARICUTIN VOLCANO FROM APRIL 1 TO JULY 31, 1947

Ray E. Wilcox

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A record of the activity of Parícutin Volcano, Michoacán, Mexico, covering the period April 1 to July 31, 1947, is shown in the diagram of eruptive characteristics, Figure 1, and the area covered by lava is shown in the map, Figure 2. An explanatory discussion of the diagram of eruptive characteristics is given in the first report of the present series [see "References" at end of paper, WILCOX, 1947a]. Discontinuity of data of Figure 1 for June and July is caused by weather conditions that made observations less continuous than usual.

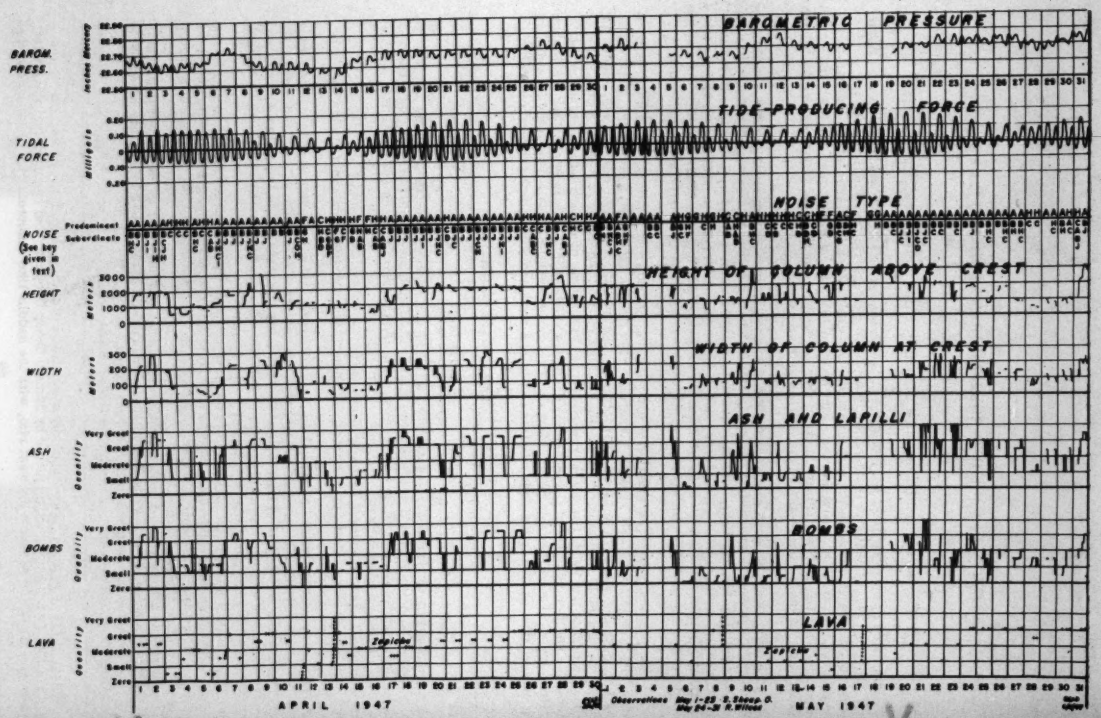
Preliminary study of the data does not seem to show a consistent correlation of the activity of Parícutin Volcano with barometric pressure, tide-producing force, or local earthquakes during the period April 1 to July 31, 1947. During a few intervals the most intense pyroclastic activity corresponded to high barometric pressures, and a suggestion of correlation with tide-producing force occurred April 16 to 27 when the intensity of the eruption rose and fell, often with the rise and fall of tide-producing force. Definite conclusions must await a thorough analysis of all the data.

Activity of the cone--The eruption of pyroclastics, as shown in Figure 1, was very erratic in May, June, and July. Periods of intense eruption were seldom more than a few hours' duration, and the changes from weak to intense pyroclastic eruption and vice versa were usually sudden and without recognizable preliminary symptoms. The quantity and intensity of emission of vapors from the crater was generally great, regardless of the amounts of pyroclastics, except during July. The position and size of the individual discharge vents within the crater changed from time to time, and occasionally one vent would be erupting pyroclastics while another would be discharging only vapors. A key to the code relating to noise is repeated with minor revisions in Table 1.

Table 1--Noise types of Figure 1

Type	Description
A	Soft surging or swishing noise, barely audible at distances greater than one km
B	Loud and more profound surging noise than A, similar to heavy surf breaking on a shore
C	Thunder-like noise, rolling and reverberating, lasting two to fifteen seconds, often initiated by heavier explosions
D	Noise like that of muffled heavy artillery fire
E	Noise like that of light artillery fire, sharper than D and often producing visible compression waves
F	A steady rushing roar, like the jet emission of steam under very high pressure, continuing uninterrupted for periods greater than one minute
G	Undulating noise of jet emission of steam under high pressure; this type often sounds like a distant, fast-moving railroad train, with the intensity and quality of the noise changing as the train passes irregularities in the terrain
H	Intermittent noise of jet emission of steam, usually harsher in quality than F or G; alternating periods of noise and silence range from three to sixty seconds in length, and at times are sufficiently regular in periodicity to resemble the slow chugging of a hard-pulling freight engine
I	Noise like that of a pistol shot, caused by discharge of electricity in the eruptive column
J	Flat slap noise, caused by falling volcanic bombs; with many bombs falling, the noise resembles the confused beat of horses' hoofs.
O	Complete lack of noise for more than five minutes

Form of the cone and crater--The only observation of the interior of the crater during the period of this report was made on June 9 by Samuel Shoup Oropeza, who reported that the crater bottom was about 150 m below the west rim, with the saddle-like southwest rim being especially


BAROMETRIC PRESSURE
BAROM. PRESS.
Inches Mercury
TIDE-PRODUCING FORCE
TIDAL FORCE
Milligals
NOISE TYPE
NOISE (See key given in text)
Predominant
Subordinate
HEIGHT OF COLUMN ABOVE CREST
HEIGHT
Meters
WIDTH OF COLUMN AT CREST
WIDTH
Meters
ASH AND LAPILLI
ASH
Quantity
Very Great
Great
Moderate
Small
Zero
BOMBS
BOMBS
LAVA
LAVA
Zapicho
APRIL 1947
MAY 1947
Observations

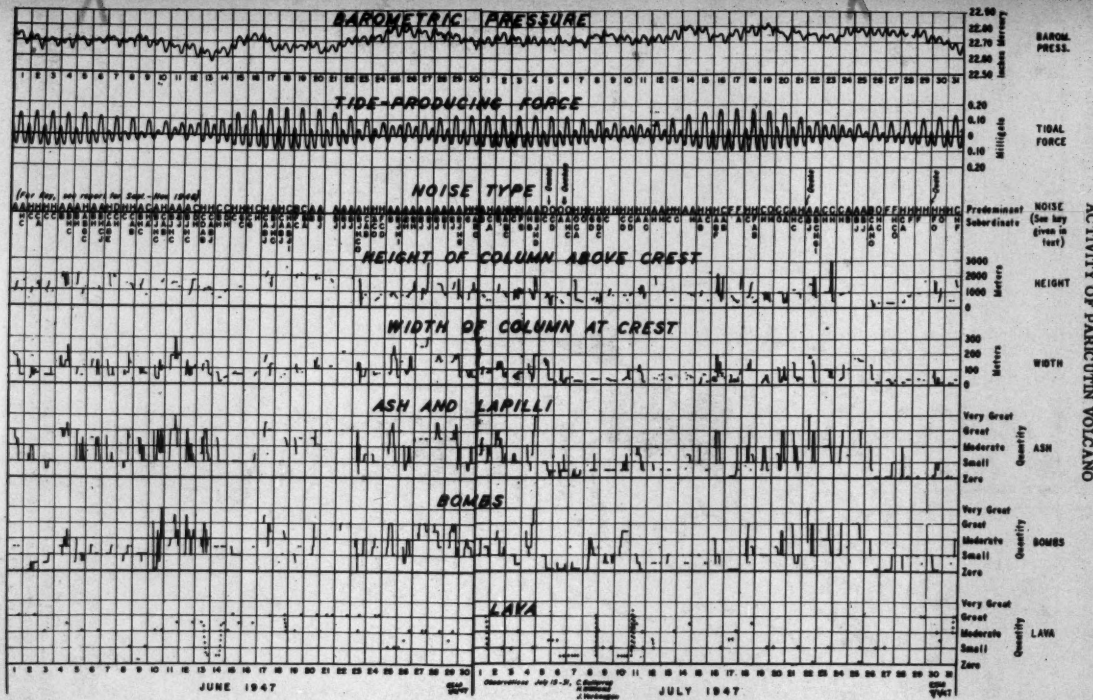


Fig. 1--Eruptive characteristics of Parícutin Volcano from April 1 to July 31, 1947

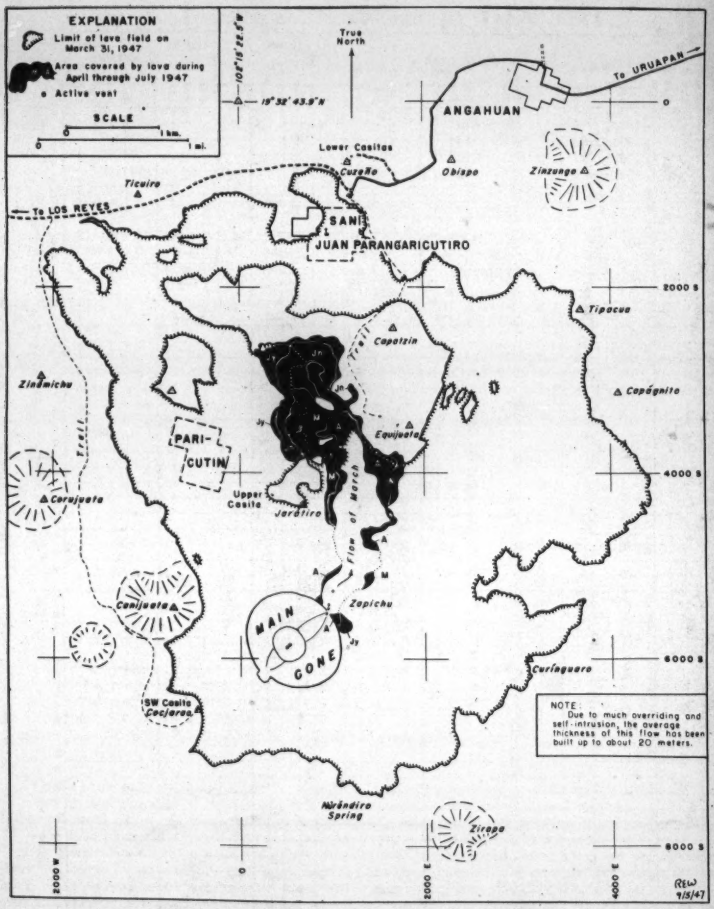


Fig. 2--Lava flows, Paricutin Volcano from April 1 to July 31, 1947

sharp. Three vents about two m in diameter were situated somewhat southwest of the geometrical center of the crater along a NE-SW line about 15 m in length. A fourth vent, one m in diameter, was offset about eight m to the southeast of the southwest portion of this line.

The external form of the cone did not change except for occasional minor faulting and sagging of the northeast and southwest segments, which had slumped initially in January 1947. Elevations of points on the rim, determined by alidade from Cuzeno Station with an estimated accuracy of $\pm$1.5 m are given in Table 2.

Table 2--Elevations of points on the crater rim

Date	West peak	Lowest point in NE rim	East peak
1947	m	m	m
April 1	2756.7	2701.1	2760.1
April 30	2756.7	2731.8	2761.5
May 31	2754.9	2733.6	2759.7
June 30	2755.9	2737.2	2759.5
July 31	....	....	....

The abnormally great increase in height of the lowest point on the northeast rim during April represents merely the filling of a notch formed in March when a narrow portion of the rim subsided. On July 5 a plug-like portion of the northeast flank slightly below the rim subsided to leave a pit about ten m deep and 20 m in diameter. Falling pyroclastics had nearly filled this pit by the end of July. Although vapors issued from the pit, sometimes as weak puffs related to the explosions in the main crater, no forcible eruption of vapors or pyroclastics occurred from it.

The piling up of successive lava flows about the base of the cone has caused a marked decrease in relief of the cone during the last two years, in spite of the actual slow increase in altitude of the rim, as illustrated by the data of Table 3.

Table 3--Changes in elevation of rim and base of cone from May 1945 to June 1947

Location	Elevation		Increase
	May 1945	June 1947	
	m	m	m
Rim, West peak	2730	2756	26
NE saddle	2710	2737	27
East peak	2740	2760	20
Base, West base	2490	2584	94
NE base	2460	2540	80
SW base	2545	2638	93

Activity of the lava vents--Variations in the activity of the lava vents are shown in Figure 1. Only the "Zapichu" vents, located along a fracture zone bearing slightly east of north from the northeast base of the cone (see Fig. 2), produced lava during April 1 to July 31, and the rate of lava production was more erratic than usual. The amount of lava erupted during July was the smallest observed for any similar period since the present program of observation began in September 1946.

From April 1 to 13 the two lava vents closest to the cone on the fracture zone were active. On April 13 gigantic fountaining from the vent at the immediate northeast base marked its temporary cessation of activity, and at the same time the vent situated about 150 m out from the base of the cone was opened with one single fountain surge, and this vent became the chief lava producer during the remainder of the period. The persistance of the location of the outermost vent, despite strong fluctuations in volume of flow, makes it probable that this is a true "primary" vent, as defined by BULLARD [1947], rather than simply the mouth of a crusted-over lava stream. Fumes issued strongly from the fracture zone connecting it with the base of the cone, and at intervals the minor vents situated along this fracture zone had brief periods of activity. The intermittent activity of the vent at the immediate northeast base of the cone, notably the fountaining of lava of May 8, 17, June 14, 18, and 22, July 8 and 11, built up the area until the section of cone pyroclastics that had been shoved outward with the original opening of the vent in January 1947 was almost buried.

Activity of the lava flows--The area covered by lava from April 1 to July 31, 1947 is shown on the map, Figure 2. Except for the limited spreading of the lava around the vent at the northeast base of the cone, the lava continued to flow northward in the channel established in March. The fronts of this main flow were extended, the lower reaches widened, and the thickness of the flow greatly increased by overriding and self-intrusion. During May the front split into four tongues that cascaded down the Jarâtiro-Capatzin scarp, piling up and coalescing at the base. The spread

of the flow eastward around Equijuata ceased in May. During June the main front spread westward and northward, augmenting its thickness over the areas already covered, and in July the rate of advance of the front greatly decreased. With the passage of the flow down the Jarátiro-Capatzin scarp, the trail to the Upper Casita at Jarátiro was cut, and approach to the Upper Casita and the cone became more difficult.

The surface of this flow, as most Parícutin flows, was composed of a reddish rubble, which tumbled down the front, together with blocks broken off the incandescent core as the flow moved.

Weather data--The results of daily weather observations at Cuzeño Station are summarized in Table 4. Barometric pressures in Figure 1 for the period April 1 to 23 were taken from hourly readings of a portable Tycos aneroid, and from April 24 onward were taken from a Fries Station Barograph, adjusted to agree with the Tycos aneroid.

Table 4--Monthly summaries of daily weather observations, Cuzeño Station, Parícutin Volcano

Month	Temperature		Rain		Ash		Minimum relative humidity	Average upper wind direction
	Max	Min	Total	Max	Total	Max		
1947	°C	°C	mm	mm	mm	mm	pct	
April	33.1	3.9	2.0	2.0	3.3	1.1	9	S
May	31.8	6.6	103.1	24.3	3.8	1.5	30	insuf. data
June	25.6	10.0	301.2	38.5	0.0	0.0	50	ESE
July	24.3	9.2	276.2	31.9	0.0	0.0	57	E

Acknowledgments--The author would like to thank Samuel Shoup Oropeza, observer for the Instituto Geológico de México, and Celedonio Gutiérrez for constant aid as fellow workers. During the writer's absences from the volcano the record of the activity for May 1 to 23, as it appears in Figure 1, was made by Samuel Shoup Oropeza, and that for July 15 to 31 was made by Celedonio Gutiérrez, supplemented by the observations of Howel Williams and Jean Verhoogen of the University of California. The writer is also indebted to Howel Williams for the delineation of the lava front as it existed July 31.

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U. S. Geological Survey,
Washington 25, D. C.

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ACTIVITY OF PARÍCUTIN VOLCANO FROM AUGUST 1 TO NOVEMBER 30, 1947

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(Published by permission of the Director, U. S. Geological Survey, and Chief of Department of Geology, Secretaria Recursos Hidráulicos de México)

A record of the activity of Parícutin Volcano, Michoacán, México, covering the period August 1 to November 30, 1947, is shown in the diagram of eruptive characteristics (see Fig. 1), and the areas covered by lava during this period are shown on the map in Figure 2. The reader is referred to previous reports [see "References" at end of paper, WILCOX, 1947 and 1948] for explanatory discussion of the diagram of eruptive characteristics. Data of barometric pressure, tide-producing force, and earthquakes (felt locally) are included in Figure 1 but will not be interpreted until more data has accumulated. A description of the lettered noise types was given earlier [WILCOX, 1948].

Activity of the cone--As illustrated in Figure 1, the erratic variations in the eruption of pyroclastics continued during the period, August through November, with the periods of strong eruption of pyroclastics lengthening somewhat during October and November. At intervals, especially during August and September, several crater vents were active simultaneously, with differing amounts of pyroclastics and vapors issuing from the separate vents.

On August 10 and 11, extraordinarily intense explosions occurred, ejecting an ultra-fine buff-colored ash in addition to the normal pyroclastics. This ash, falling in the northern sector, blighted vegetation for a distance of ten km from the volcano. It is possible that the blighting action was caused by the smothering of the plants by the ultra-fine ash. A sample of the still undisturbed ash was collected August 15 and tested for chlorine, sulfurous and sulfuric ions, none of which was found to be present. It is possible that they might have escaped during the four days following the ashfall.

The explosions of August 10 and 11 were reported to have been of great strength, projecting bombs several hundred meters beyond the base of the cone. Frequent jumps of the barograph pen of 0.05 inches of mercury and greater were recorded as a result of the compression waves from the explosions. On September 26, a single gigantic explosion threw bombs as far as the base of Canijuata, a distance of one km from the center of the main cone.

A temporary pyroclastic vent was opened near the top of the southwest slump segment early in November (see Fig. 2). On November 6, copious white vapors were observed issuing from the site, and on November 7, one short burst of ash and bombs was erupted almost without noise, leaving a shallow crater from which white vapors issued intermittently. On November 15, another brief eruption of pyroclastics was observed. Subsequently no more than vapors were observed to be erupted.

Form of the cone and crater--An inner crater rim, which for some months had been building up within the main crater, passed the level of the outer rim about October 20. Thenceforth, with the continued growth of this inner rim, the altitude of the cone increased rapidly, as shown in Table 1. The diameter of the inner rim on November 30 was about 220 m, compared to the 300 m diameter of the outer rim, by then, almost obliterated.

A steep-walled pit, about six m in diameter and eight m in depth, formed September 4 at the site of the similar pit of July 5 near the top of the northeast slump segment, but was refilled with pyroclastics within three weeks. In an analogous position on the southwest slump segment an intermittently active pyroclastic vent was initiated early in November (see Activity of the cone), forming a shallow crater never more than four m in depth when observed. By November 30 it had been filled with pyroclastics. The bordering fractures of the northeast slump segment were renewed from time to time but no appreciable downward movement of the segment was observed.

Activity of the lava vents--Figure 1 shows the rates of lava production. The southwest lava vents (Puertecito and Ahuan vents), because of their position, were not as continuously observed as the northeast vents (Zapichu vents). The quantities plotted for the evening observations of the southwest vents were based on the intensity of reflected glow on the vent vapors and clouds and cannot be as reliable as the direct observations.

On August 11 the northeast vents increased thier activity, and on August 14 the Puertecito vent, at the base of the southwest slump segment, became strongly active but by August 28 had declined

Table 1--Elevations above sea level of points on the crater rim

Date	West peak	Lowest point in NE rim	East peak
1947	m	m	m
August 31	...	2738.8	...
September 4	2756.6	2740.3	2758.8
September 30	2757.4	2746.3	2760.6
October 31	2773.2	2768.1	2774.2
November 29	2775.4	2768.9	2775.4

to only slight activity. On September 1 the Ahuan lava vent, about 100 m south of the Puertecito vent at the southwest base of the cone, opened and was thereafter the chief lava producer. The northeast vents showed only small activity during September and none at all after October 9.

BAROMETRIC PRESSURE
Inches of Mercury
TIDE-PRODUCING FORCE
Milligals
NOISE TYPE
HEIGHT OF COLUMN ABOVE RIM
Meters
WIDTH OF COLUMN AT RIM
Meters
ASH AND LAPILLI
Quantity
BOMBS
Quantity
LAVA
Quantity
Very Great
Great
Moderate
Small
Zero
AUGUST 1947
SEPTEMBER 1947

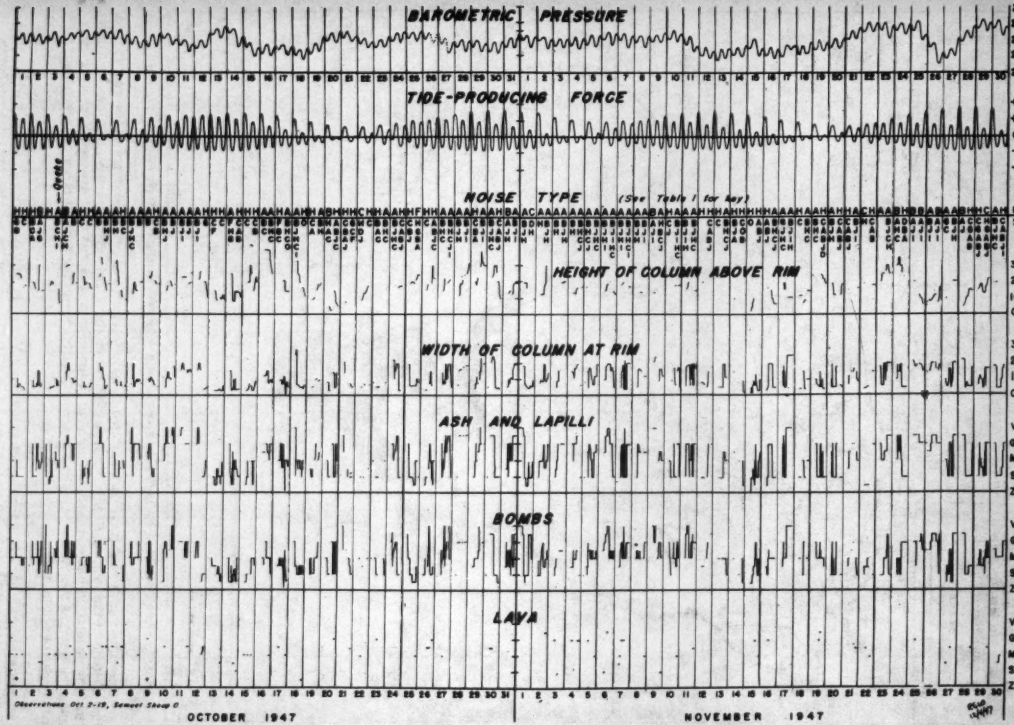

Fig. 1--Eruptive characteristics of Parícutin Volcano from August 1 to November 30, 1947

Fig. 2--Area covered by lava flows; Parícutin Volcano, August 1 to November 30, 1947

The Ahuan lava vent steadily increased in height because of brief floodings of the vent mound. The altitude of the vent on November 7 was 2654.2 m above sea level, 8.8 m higher than on August 28. The persistent channel leading south out of the vent mound was well exposed November 30 when the level of the lava stream had dropped greatly, revealing a channel ten m in width and more than seven m deep.

Activity of the lava flows--The long flow from March to July (see Fig. 2), which had proceeded north from the northeast lava vents, slowed to a virtual stop during August, although negligible movements continued during September. On August 16 a new flow started east from the outermost

The initial flow from the Puertecito vent, at the base of the southwest slump segment, started August 14 and proceeded rapidly around the west base of the cone, following the drained channel of the flow from January to March. Its movement stopped August 19 while lava continued to spread south and southeast from the vent during the remainder of August. The flow from the Ahuan vent started September 1 and spread with great rapidity on a wide front to the southeast. Although the whole of the front remained active during October and November, the forward advance became subordinate to the process of building up the thickness of the flow. The movement of this flow, instead of being in a few selected channels, was radially from the base of the vent mound, forming a surface of large concentric waves. The front was usually from ten to 13 m in height and composed of blocky reddish lava. A noteworthy characteristic of the front was the continuous snapping and popping noise of small flakes spalling off the cooling blocks. On November 30 all of the front showed activity, and the most rapid movement was in the lobe spreading northeast. The southeast lobe had approached to within 30 m of Nurêndiro Spring.

A new trail was built during November across the lava field to the upper Casita at Jarátiro. A deep gully formed during the wet season made it necessary to reach the southwest Casita by crossing the lava between Canijuata and the main cone rather than circling behind Canijuata.

Weather data--The results of daily weather observations at Cuzeño station are summarized in Table 2. The average upper wind direction expresses the average direction of the winds carrying the major portion of erupted ash and vapors. Barometric pressures are shown in Figure 1.

Table 2--Monthly summaries of daily weather observations, Cuzeño station

Month	Temperature		Rain		Ash		Minimum humidity	Average upper wind direction
	Max.	Min.	Total	Max.	Total	Max.		
1947	°C	°C	mm	mm	mm	mm	pct	
Aug.	25.6	7.9	277.7	40.0	1.7	1.0	57	E
Sept.	24.5	6.9	107.0	20.7	0.4	0.3	25	E
Oct.	25.2	8.0	192.9	42.0	1.1	1.0	45	ESE
Nov.	24.8	4.5	72.0	45.0	12.4	2.0	32	SSW

Acknowledgments--Acknowledgment is made to Celedonio Gutiérrez for much aid in the field and for observations from August 1 to 14, as well as other brief intervals. Acknowledgment is also made to the United States Coast and Geodetic Survey for computed maximum and minimum values of tide-producing force as plotted on Figure 1.

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Washington 25, D. C.

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Transactions, American Geophysical Union Volume 29, Number 1 February 1948

FLUCTUATIONS IN CONCENTRATION OF DISSOLVED SOLIDS OF SOME SOUTHWESTERN STREAMS

John D. Hem

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Abstract--The concentration of dissolved solids in waters of streams of the Southwestern United States fluctuates widely as the stream discharge changes. These fluctuations may be extensive in a period of a few days or even a few hours. Data in this paper show the extent of the day-to-day changes in specific conductance and discharge of the Rio Grande at San Acacia, New Mexico, during the spring run-off period of 1945. Data also are presented to show rapid fluctuations in concentration for the Pecos River near Artesia, New Mexico, the Gila River near Bylas, Arizona, and the Rio Grande at San Acacia during typical summer months. Hourly changes in chloride and discharge are shown for a day of approximately normal flow for the Pecos River near Malaga, New Mexico, and for a 36-hour period of extremely low flow for the Gila River near Fort Thomas, Arizona.

Introduction--Studies of the chemical character of surface waters of the United States have shown that the concentrations of dissolved mineral matter in the water of a stream at any point are likely to be variable over a period of time. That such variations should occur is to be expected, but in most streams of the Southwest these variations are unusually large and may occur rapidly. Records of discharge and analyses of water samples in the files of the United States Geological Survey show large fluctuations of dissolved solids for waters of the Rio Grande and Pecos River in New Mexico and the Gila River in Arizona. In this respect these streams are typical of the rivers of the Southwestern United States.

Concentrations of dissolved solids are expressed in terms of specific conductance ($K \times 10^5$ mhos at 25°C) in some of the illustrations in this paper. Conductance determinations provide approximate values for the total dissolved mineral matter contained in a water. For the waters of the Rio Grande and those of the Pecos River, here discussed, the conductance value multiplied by a factor of seven gives approximately the concentration of dissolved solids in parts per million. For the waters of the Gila River this factor is nearer six. For some of the waters containing large proportions of chloride, the concentrations of chloride are expressed as parts per million (ppm).

Typical seasonal changes--Variations of dissolved solids content of the waters of all streams generally are closely associated with variations in the river discharge. Figure 1 illustrates a characteristic seasonal trend with content of dissolved matter as represented by specific conductance of daily samples plotted with mean daily discharge in cfs for the Rio Grande at San Acacia, New Mexico (about 50 miles upstream from the head of Elephant Butte Reservoir), for the months of April, May, and June, 1945. The high discharges at this station during the period were caused by runoff from melting snow in the headwaters of the river. The conductance values ranged from a minimum of 30.4 on May 27 during the period of high flow, to about 70 both before and after the high water period. The tendency for the lowest concentrations of dissolved matter to be contained in the water of sustained high stages during spring or winter runoff periods is characteristic of most streams of the Southwest. During the periods of highest runoff at this time of the year the concentration of dissolved solids tends to remain relatively constant.

In Arizona and New Mexico, particularly at elevations below about 7000 feet, a considerable part of the annual precipitation is received in local summer showers which sometimes cause violent flash floods. Hence the discharges of streams draining the lower areas tend to fluctuate widely during the summer and the accompanying changes in dissolved solids concentration of the water are very marked. Figure 2 shows the discharge and specific conductance for the Gila River at Bylas, Arizona, near the head of San Carlos Reservoir, for August 1943. The low-flow waters of the river in this area consist largely of ground-water seepage which contains large amounts of dissolved matter. Flood flows resulting from the summer rainstorms in the drainage basin above Bylas consist of water of low to moderate dissolved solids content. The dilute flood waters mixing in different proportions with the small constant inflow of highly mineralized ground water

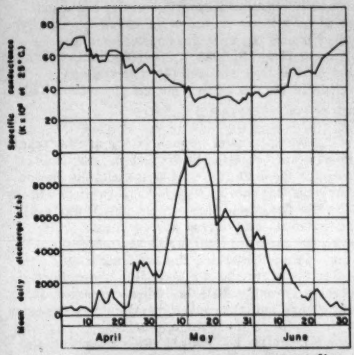

Fig. 1--Daily conductance and mean daily discharge of Rio Grande at San Acacia, New Mexico; 1945

caused wide variations in the concentration of dissolved matter in the river waters during the month. Because of the flashy nature of the flood-water flow, the river stage changes rapidly during rainy periods with accompanying changes in conductance of 100 per cent or more in a few hours. During August 1943 there were six small floods at this station, during each of which the conductance of the water was lowered. After each flood the conductance of the water increased again as the river flow decreased. The conductance of daily samples during the month ranged from a minimum of 73.0 on August 11 to a maximum of 404 on August 1.

Similar fluctuations also are typical of the Pecos River as shown by the graph of discharge and conductance of the Pecos River near Artesia, New Mexico for August 1939, included in Figure 2. The ground water entering the Pecos River above Artesia is highly mineralized but because of the large areas of soluble rocks exposed in the Pecos River basin, flood flows reaching the Artesia gaging station usually contain larger concentrations of dissolved matter than flood waters in the Gila River basin. The conductance values at the Artesia station during the month ranged from 115 on August 4 to 677 on August 31. During each of three small floods that month there

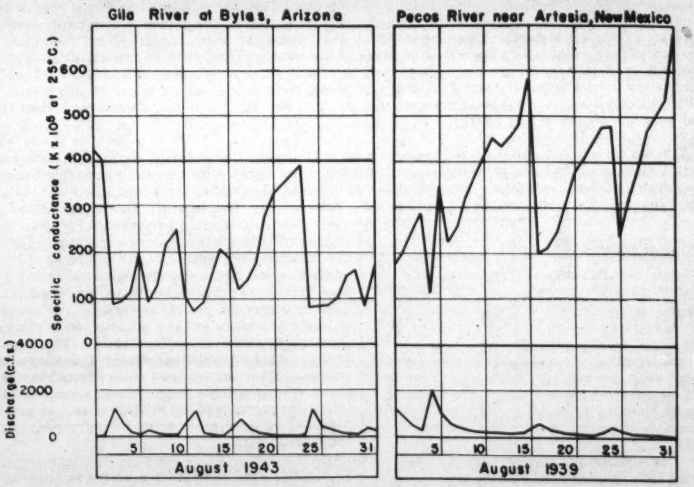

Fig. 2--Daily conductance and the mean daily discharge of two southwestern streams

was a marked reduction in the concentration of the river water, followed in each instance by an increase in concentration as the flow decreased.

Rapid fluctuations--A sampling program which provides for the collection of a single daily sample is inadequate to show the changes taking place in these streams when discharges are fluctuating rapidly. During the summer of 1946 a more comprehensive sampling program was

begun at the San Acacia gaging station on the Rio Grande to obtain information on the sediment load of the stream as well as the chemical character of its waters, samples being taken three or more times daily when the river was in flood. Figure 3 shows the specific conductance and instantaneous discharge at times of sampling from August 11 to 19, 1946. The wide fluctuations of concentration of the water at this station during the period contrast sharply with the comparatively minor fluctuations shown for the same station in Figure 1 for a period of sustained high flow.

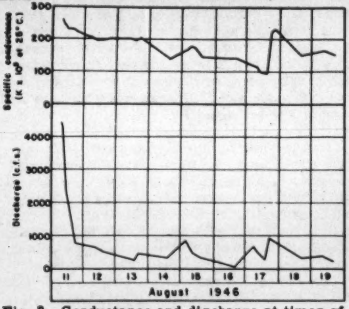

Fig. 3--Conductance and discharge at times of sampling of Rio Grande at San Acacia, New Mexico

The variations of concentration at San Acacia differ in their relation to discharge from those shown for the Gila River at Bylas and the Pecos River near Artesia in Figure 2. Low-flow waters of the Rio Grande at this station are of moderate concentration, and during some periods flood flows may consist of rather highly mineralized water. Two tributaries, the Rio Puerco and the Rio Salado, enter the Rio Grande a short distance upstream from San Acacia. These streams drain areas where soluble rock formations are exposed and flood waters from them generally are rather highly mineralized. Several other tributaries of the Rio Grande also contribute highly mineralized flood waters, but most of the tributaries carry flood waters of low concentration of dissolved solids. Hence an increase in river discharge at San Acacia may be accompanied by either an increase or a decrease in the dissolved solids content of the water, depending on the source of the rise. During the period of nine days covered in Figure 3 the conductance ranged from 97.7 to 261. August 17 shows a particularly wide fluctuation. Early on this day a flood flow of water of low concentration reduced the conductance of the water to the minimum for the nine-day period. During the afternoon a second flood flow reached the station from a different part of the drainage basin, consisting of highly mineralized water. This second rise caused the conductance of the water to rise to 232, an increase of more than 100 per cent in a period of four hours.

From time to time detailed studies have been made by the United States Geological Survey to indicate the amount of change in concentration that may be expected in a day at a sampling point under normal flow conditions. Figure 4 shows the results of sampling the Pecos River at hourly and half-hourly intervals on July 13 and 14, 1937, near Malaga, New Mexico. During the period the river discharge fluctuated considerably, possibly because of reservoir regulation upstream, and the chloride rose sharply at the beginning of the study to a maximum slightly over 1200 ppm. It then decreased progressively to a minimum of 1060 ppm near the end of the period. The lowest chloride concentration was not reached until after the highest discharge had occurred. The causes of the chloride fluctuations during this study are complex, involving changes in the amount of the river water available to dilute saline ground-water inflows in the area of the study, solution of salt deposits along the river channel by the increased flow, and other factors.

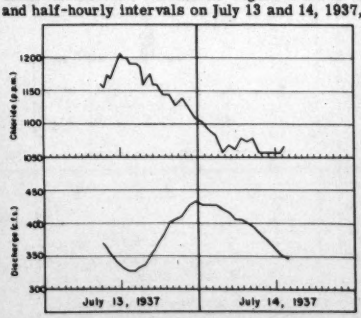

Fig. 4--Hourly chloride concentration and hourly discharge of Pecos River; 4.25 miles below gaging station near Malaga, New Mexico

During 1943 and 1944 the United States Geological Survey made a study of the use of water by river-bottom growth in the Safford Valley of the Gila River in southeastern Arizona. During this investigation and an earlier one in the same area it was observed that when the river reached extremely low stages during extended periods of fair weather in the spring and early summer, there was a diurnal fluctuation in flow at some of the gaging stations along the stream. It is believed that these fluctuations result at least in part from transpiration by plants growing in the river

bottom in those areas where the river receives seepage inflow from the ground-water reservoir. During the day the plants transpire water rapidly, thus lowering the water table and reducing inflow to the river, but during the hours of darkness when transpiration is at a low rate the water table rises again and inflow to the river increases [see "Reference" at end of paper, TURNER, 1941, p. 18].

In order to learn whether these changes in river discharge were accompanied by changes in concentration of dissolved matter in the water, samples were taken hourly for a period of 36 hours on June 22 and 23, 1944 at two points on the Gila River between Fort Thomas and Geronimo, Arizona. River flow was measured at both points by means of low-flow gaging stations. In the area where the experiments were conducted the Gila River receives inflow from the ground-water reservoir. Dense growths of transpiring vegetation, mostly salt cedar (Tamarix gallica) occur on both sides of the river channel. During June the river flow in the area gradually decreased until it amounted to less than one cfs in places. Part of the river channel, usually a strip about 50 feet wide, was kept continuously moist by ground-water seepage, with a small stream of moving water in the lowest part of the channel, and in a few places there were shallow pools of standing or slowly moving water.

The results of the study at the station near Fort Thomas (upper station) are shown in Figure 5. The chloride concentration of the water shows an apparent cyclic fluctuation, nearly in phase with the discharge cycle. The maximum chloride concentration, 2690 ppm, coincides with the maximum discharge, and the minimum chloride concentration, 2610 ppm, coincides with the minimum discharge. The diurnal changes in chloride concentration at the lower station were less extensive but followed a somewhat similar pattern.

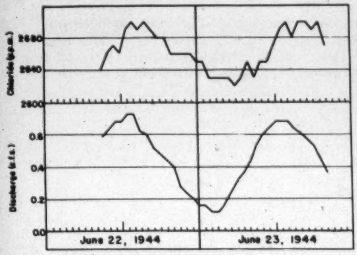

Fig. 5--Hourly chloride concentration and hourly discharge of Gila River; 1.8 miles below Fort Thomas, Arizona

The exact cause of the diurnal chloride fluctuation is not known and may be a combination of several factors. Probably the simplest explanation is as follows: During hours of lowest flow, part of the gound water seeping into the river channel was evaporated from the wetted sands of the channel, leaving behind its dissolved matter and causing an accumulation of soluble salts at the ground surface. When the water level rose with the increase in river flow, this soluble matter was at least partly redissolved, thus increasing the concentration of the dissolved matter in the water of the river at the high points of the discharge cycle. Considerable quantities of salt crust were visible in the river channel in the area where the study was made.

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DISCUSSION

C. S. Scofield (U. S. Geological Survey, Washington, D. C.)--This paper calls attention to a phenomenon that is characteristic of many streams of arid regions. In these streams the concentration of dissolved material ranges between wide limits seasonally and during shorter periods associated with rainfall. High concentrations may occur (a) in the early stages of a flash flood which carries salt dissolved from the surface soil by the first of the rain, and (b) during drought periods when the stream discharge is chiefly from ground-water seepage, often rich in salts.

One of the major objectives of an investigation of salinity conditions in streams used for irrigation is to evaluate the annual or seasonal salt burden of the stream at the successive gaging stations in

order to determine the direction and rate of change in these conditions over a period of years. In such an investigation the accuracy of the work depends upon a regimen of sampling that will afford a true representation of the actual conditions of salinity during the critical periods of the sudden changes in the volume of discharge.

At some of the important gaging stations on western streams there is need for even more detailed information as to the changes in salinity conditions during the periods of flash floods. This need might be met by installing a conductivity unit at a gaging station connected with a recorder. We now have in general use automatic recorders for the volume of discharge. The installation of automatic recorders for conductivity, supplemented by sampling, would afford a sound basis for estimating the salt burden of a stream at its successive gaging stations.

The charts in Hem's paper call for comment. In Figures 1 to 3, the vertical scales for discharge and for conductance are of comparable magnitude. But in Figures 4 and 5 the scale for concentration (chloride) seems too much exaggerated. Thus in Figure 4 the scale for discharge covers a range of 50 per cent of the base while the scale for concentration covers a range of only five per cent of the base. In Figure 5 the contrast is even greater. The recorded discharge ranges from 0.1 to 0.7 cfs, while the recorded concentration from 2620 to 2190 ppm. These reported differences in concentration are relatively very small.

It should be noted that the fluctuations in volume of discharge and in salinity condition in western streams occur chiefly in streams that are not controlled by storage works. The construction and operation of reservoirs along these streams and their tributaries serve not only to regulate the volume of discharge but also to diminish most effectively the fluctuations in the concentration of dissolved solids.

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THE INDUCED INFILTRATION OF RIVER WATER TO WELLS

Raphael G. Kazmann

Abstract--Two methods are proposed for determining whether water from a surface source will infiltrate to an adjacent aquifer if wells are pumped at the site tested. One method is based on steady flow before the onset of pumping, whereas the other is based on steady flow occurring during a pumping test. As the basis of analysis both methods rely on contour maps of the piezometric surface or changes in the piezometric surface. The maximum rate of infiltration from a surface source is not involved in either of these methods. The only answer sought is whether infiltration will occur after pumping begins. As a by-product of this analysis a method of determining the effective distance to the line of recharge is also given. Illustrations and actual maps of piezometric surfaces are included to bring out the fundamental principles described in the text.

Introduction

The tendency to turn to ground water as the answer to pressing industrial, municipal, and agricultural water-supply problems in the past several years has caused ground-water hydrologists to concentrate their studies upon the basic elements which lead to a perennial water supply [see "References" at end of paper, MEINZER, 1946].

As all ground water is derived from precipitation which has percolated in one way or another to the water-bearing formation, the first element to be considered in the study of a particular ground-water area is the above-ground source of recharge in the area.

This above-ground source of recharge may be the precipitation falling on the outcrop of the aquifer or it may be a permanent body of surface water such as a lake or stream overlying the outcrop of the aquifer. Regardless of its form, the source of recharge governs the magnitude of the perennial supply obtainable from any aquifer.

At present, determination of the perennial supply available from precipitation on the outcrop of the aquifer is time consuming, with the precipitation upon a relatively small area as the limiting factor. It is more satisfactory to base a ground-water supply on infiltration from a surface source which is supplied by the precipitation over a relatively large drainage area, such as a stream or lake. This method generally results in a larger perennial supply and is becoming more widespread as the application of the engineering principles involved becomes generally known.

The problem is to determine in advance of permanent construction whether or not surface water will infiltrate into the aquifer in response to hydraulic gradients created by pumping wells. Infiltration may be prevented by deposits of silt in rivers and lakes or by lenses of clay or cemented materials existing immediately below the stream or lake bed. The most critical examination of the surface geology, or even the geology as given by logs of test wells cannot give a conclusive answer to the infiltration problem. However, several geophysical methods have been developed recently to give a definite answer. These are outlined in the following paragraphs.

Methods of existing ground-water gradients

Water table sloping away from the stream--When a surface source, a stream for example, is feeding water to an aquifer, a hydraulic gradient is established from the stream landward. If observation wells are constructed in the sand and gravel deposits adjoining such a stream, a water-level contour map (sometimes called a piezometric map) drawn on the basis of depth-to-water measurements in the observation wells will show a hydraulic gradient from the stream and indicate the direction of water movement. The slope of the piezometric surface together with the transmissibility of the aquifer enables the hydrologist to compute the rate at which water is entering the aquifer from the stream. It may be safely stated that, under water-table conditions, when a hydraulic gradient exists away from a river and into an aquifer, river water is infiltrating into the aquifer.

Water table sloping toward the stream--It is submitted that, when dealing with a flow of ground water through sands and gravels, one-way valves are not encountered. If water will flow through a porous medium in one direction, it will flow in the opposite direction when the hydraulic gradients are reversed.

Therefore, in general, assuming that the bottom of the aquifer is at a lower elevation than the stream level and the ground water in an aquifer is feeding a nearby stream, pumping wells in the aquifer will reverse the gradients and cause the stream to feed the aquifer.

If a ground-water contour map shows that water is entering a stream or lake from an aquifer, it may be tentatively concluded that infiltration from the stream will occur if wells are constructed in the aquifer and pumped. Figure 1 shows a typical ground-water contour map of an aquifer of limited extent near the Chippewa River about a mile from Mount Pleasant, Michigan. The water-table contours indicate that water from the aquifer is entering the river. On the basis of this contour map it is evident that a well field located in this area will induce the infiltration of water from the stream into the aquifer.

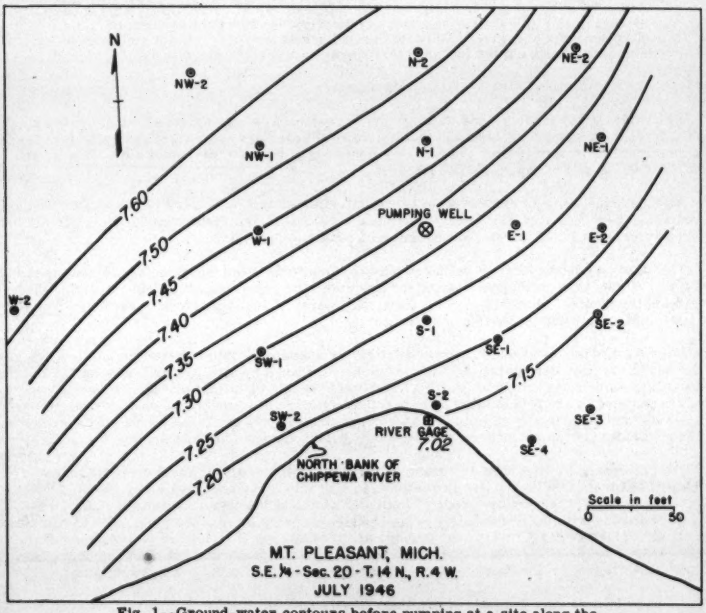

Fig. 1--Ground-water contours before pumping at a site along the Chippewa River near Mount Pleasant, Michigan

Pumping test methods

Piezometric maps--Whether or not water will infiltrate from the stream into an aquifer by the action of a well field can be best determined by conducting a pumping test near the stream. This requires construction of one well from which water is pumped at a constant rate during the test and construction of several observation wells in which frequent measurements of water levels are made as pumping continues.

One method of analyzing data obtained from such a pumping test near a stream is to draw a contour map of drawdowns occurring in the vicinity of the pumping well. Such a map, drawn on a

theoretical basis by the use of the Theis method [THEIS, 1941; KAZMANN, 1946], for a pumped well, which is 500 feet from a stream, is shown in Figure 2 (all of the usual assumptions in groundwater hydraulics have been made in computing the drawdowns for this map). As steady-state flow is involved, the storage coefficient (and its variations with time) is immaterial. The drawdown at any point is the result of the pumping of the real well at a given rate plus the negative drawdown caused by the image well which is recharging at the same rate. In constructing Figure 2 the numerical constants in the Theis formula have been chosen in such a way as to multiply the well function, $-\mathrm{Ei}(-u)$, by unity.

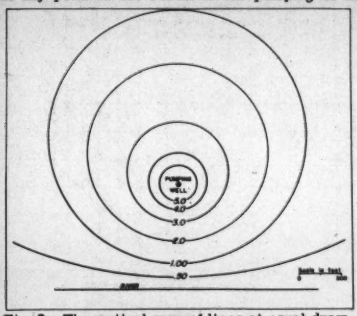

Fig. 2--Theoretical map of lines at equal drawdown near an idealized line of recharge

$$s_r = (Q/4\pi T)[-\mathrm{Ei}(-r_1^2 S/4Tt)]$$

where s_r is the drawndown caused by the real well discharging at a uniform rate Q, r_1 is the distance from the real well to the chosen point where the drawdown is measured, S is the coefficient of storage of the aquifer, t is the duration of discharge at the time the measurement was made, and T is the coefficient of transmissibility of the aquifer.

$$s_i = (Q/4\pi T)[-\mathrm{Ei}(-r_2^2 S/4Tt]$$

Where s_i is the negative drawdown caused by the image well which is recharging at a uniform rate Q, r_2 is the distance from the image well to the chosen point and all the other symbols are as previously defined

$$s_o = s_r + s_i$$

Figure 3 shows a contour map of drawdowns at the test site near Mount Pleasant, Michigan. The original slope of the piezometric surface at the same site is given in Figure 1. The similarity in form between Figures 2 and 3 is evidence that infiltration from stream flow occurs at that site when water is pumped from a well close to the stream.

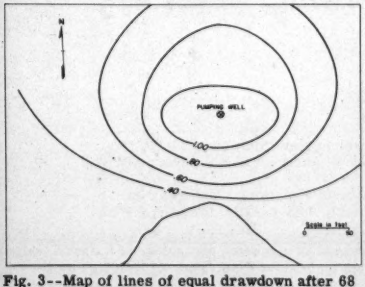

Fig. 3--Map of lines of equal drawdown after 68 hours of pumping at a site along the Chippewa River near Mount Pleasant, Michigan

Slopes--Another method of studying the data obtained by means of a pumping test is to make a semi-log plot of drawdown against distance from the pumped well. Figure 4 is a theoretical semi-log plot (using the data of Figure 2) of the profiles of the cone of depression toward the stream, parallel to the stream and away from the stream, all distances being referred to the pumping well.

The difference in slopes of the profiles toward the stream and parallel to the stream are of great significance. Had there been no source of recharge, these slopes would have been the same. The difference is the result of recharge from the stream.

Figure 5 is the plot made on the basis of measurements of water-level decline during the pumping test at Mount Pleasant, Michigan, which was mentioned earlier. The steepness of slope toward the river as compared to that in any other direction is interpreted as the existence, during pumping, of river infiltration. The possibility that differences in permeability are causing the difference in slope is so unlikely that, for practical purposes, it may be neglected. Nevertheless, a method to investigate this possibility was proposed to the writer in a personal comunication by E. W. Silitch. If, while pumping continues, the slope of the profile toward the river remains constant or becomes steeper whereas the slope parallel to the river decreases, the only possible explanation is that infiltration is occurring. For, if the difference in slopes was caused by a difference

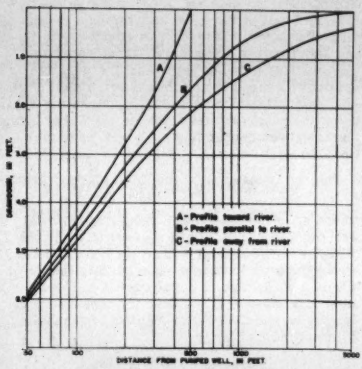

Fig. 4--Semi-log plot of data in idealized example given in Figure 2

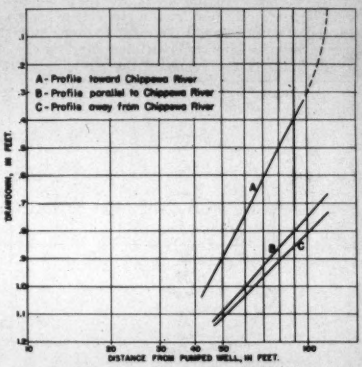
A - Profile toward Chippewa River
B - Profile parallel to Chippewa River
C - Profile away from Chippewa River
A
B
C
DISTANCE FROM PUMPED WELL, IN FEET.

Fig. 5--Semi-log plot of data obtained after 68 hours of pumping at Chippewa River site

in transmissibility, that difference should remain constant as pumping continues, it being inconceivable that the transmissibility should change significantly during the pumping test. Applying this reasoning to the data obtained at Mount Pleasant, relationships exist as shown in Table 1.

Table 1--Relationships observed during pumping test, Mount Pleasant, Michigan

Well number	Drawdown after pumping		Distance from pumped well
	6 hours[a]	68 hours[b]	
	ft	ft	ft
S - 1	0.80	0.90	50
S - 2	0.33	0.36	95
N - 1	0.96	1.11	50
N - 2	0.64	0.81	100
E - 1	0.98	1.09	50
E - 2	0.62	0.75	100

[a]Slope toward river, 0.0104 (0.47 ft difference in elevation); slope away from river, 0.0064 (0.32 ft difference in elevation); slope parallel to river, 0.0072 (0.36 ft difference in elevation).

[b]Slope toward river, 0.0120 (0.54 ft difference in elevation); slope away from river, 0.0060 (0.30 ft difference in elevation); slope parallel to river, 0.0068 (0.34 ft difference in elevation).

In short, while the slope toward the river increased as a greater percentage of the total water pumped was replaced by infiltration, the contribution from other directions, an indicated by the reduced slopes, decreased as the pumping test continued.

Determination of distance to line of recharge

It is possible to determine the approximate position of the line of recharge by finding the point of intersection of the slope of the riverward profile with the line of zero drawdown on the semi-log plot. The actual position of the line of zero drawdown must be somewhat closer to the pumping well than the position of the point of intersection. The theoretical shape of the semi-log plot as given in Figure 4 is concave upward and consequently the secant or tangent of the curve must always intersect the line of zeor drawdown outside of the actual point of zero drawdown. This method is more reliable than the one described by the writer in a previous paper [KAZMANN, 1946] because it eliminates errors arising from changes in the storage coefficient during the pumping test.

Acknowledgements

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DISCUSSION

Keith E. Anderson (Missouri Geological Survey and Water Resources, Rolla, Missouri, March 24, 1947)--This paper is an excellent summary of the important methods for determining whether infiltration of surface water will be induced into an aquifer when wells are pumped. This subject is one of timely and special importance because of the increasing realization that a large and perennial supply of ground water can often best be obtained in localities where recharge by infiltrating surface water is assured.

The author, in discussing a water table (or piezometric surface) sloping toward a stream, states that "in general, assuming that the bottom of the aquifer is at a lower elevation than the stream level and the ground water in an aquifer is feeding a nearby stream, pumping wells in the aquifer will reverse the gradients and cause the stream to feed the aquifer." This statement is indeed true, in general, yet it may be well to consider an "unfortunate" set of conditions which could exist whereby infiltration would not be induced during pumping.

Consider a case where the bottom of the aquifer is at only a slightly lower elevation than the stream level and where the pumping wells must, of necessity, be located at a considerable distance from the stream. The initial slope of the water table (or piezometric surface) is here sloping toward the stream and the aquifer is feeding the stream (see Fig. 6). As soon as pumping commences, the gradients in the vicinity of the well are steepened toward the well creating a ground-water divide between the well and the river at the edge of the cone of depression. If the transmissibility of the aquifer is low, however, it may not be possible, with the desired pumping schedule, to move this ground-water divide far enough to reverse the normal gradient at the river's edge and thus induce recharge to the aquifer from the river (see B, Fig. 6).

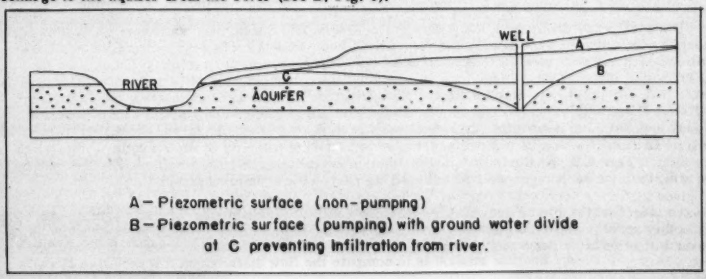

Fig. 6--Cross section showing piezometric surface

This condition, admittedly, would not be the usual case. If such a condition is known to exist, it will probably be economically feasible to go to additional expense to construct the well close to the river, with a pipe line to the point of distribution, and be certain that infiltration will afford a large and perennial supply of water.

The author has not discussed the value of chemical analyses and temperature measurements made during pumping tests to determine whether river infiltration is contributing to the discharge from the well. Such data may be valuable in substantiating the interpretations based on the study of draw downs in observation wells during pumping.

M. I. Rorabaugh (U. S. Geological Survey, Louisville, Kentucky, April 25, 1947)--The problem of establishing whether water supplies can be developed by induced infiltration from a river or lake is not nearly as simple as this paper would lead one to believe.

The fact that the water table near a lake or stream slopes away from or toward the surface supply does not in itself indicate that there is flow from the surface source into the aquifer or from the aquifer to the stream or lake. Where the bed of the river is sealed by impervious material or where the vertical permeability is very small compared to the horizontal permeability, it is possible for the ground-water flow to be under the river---the flow being toward the river on one side and away from it on the other. The water-table gradients and geologic conditions on both sides of the river should be studied; if flow is away from, or toward, the river on both sides, then it would appear that a connection exists between the river and the aquifer. No conclusion can be reached if the slope is toward the river on one side and away from the river on the other or if water-level conditions are studied on one side only.

The important things to note in studying the water table are changes in gradient (steep gradients indicate areas of poor transmissibility) and difference between river level and ground-water level.

The profile of water levels at a section perpendicular to the river should be extended toward the river. An extension that passes above the water surface of the river indicates that flow to the river is limited either by poor vertical permeability under the river bed or by a section of low horizontal permeability. An extension that passes below the river surface might indicate flow under the river. An extension that intersects the river surface would indicate that a free connection probably exists between the river and the aquifer.

Study of the relationship of changes in river level and changes in water level in the aquifer will give an additional clue as to whether a connection exists between the river and the aquifer. However, under artesian conditions, pressure changes caused by changes in river level could be transmitted to the observation wells even though the river bed was nearly impervious. Under free water-table conditions, where water-level changes require storage changes, correlation of water-level changes with river-level changes indicates that infiltration is present. Although a study of water-table conditions may be used to eliminate poor sites under certain conditions, such a study cannot in itself be used to establish definitely that infiltration is present.

I am in full agreement with the author that a pumping test is the best method of establishing whether conditions are favorable for developing an infiltration supply. Kazmann's picture for an ideal condition (with steady flow and no variations in transmissibility) is good as far as it goes. However, the problem as encountered in the field is not always as simple as the example he cites.

During the past two years, the United States Geological Survey has made two infiltration tests along the Ohio River in the Louisville, Kentucky, area. In both tests a direct conflict was found with the author's statement: "The possibility that differences in permeability are causing the difference in slope" (water-level profile on river side compared to profile on land side) "is so unlikely that, for practical purposes, it may be neglected." In the Louisville area, the Ohio River Valley is filled with 50 to 100 feet of glacial-outwash sands and gravels mixed with different amounts of clay and silt. Permeabilities do range considerably over short distances. At the first test southwest of Louisville a map of lines of equal drawdown during pumping showed a pattern similar to Kazmann's Figure 2. Analysis of flow distribution established that the steepness of the cone on the river side of the pumped well was caused, in part, by low permeabilities.

The ideal test would be one in which pumping continued until steady flow was established. This might take months or years. Comparison of changes of slopes in the various sections of the cone during the period of change in flow distribution is one method of reaching a conclusion whether infiltration is available. Another method is to compute the flow distribution for each line of wells

wells for different days of the test. By this method it is possible to evaluate the apparent transmissibility for the several lines of wells, and to draw curves of time against flow for each line of wells. If the flow-distribution curves show an increase for the river line and a decrease for the other lines, infiltration is present.

In the example cited by Kazmann, the change in slope from 6 hours to 68 hours is + 0.07 foot for the river line of wells, and - 0.02 foot for each of the other lines. It should be pointed out that the drawdown figures must be corrected for the natural buildup or recession of ground-water levels during the test, (nearly 0.5 foot in Louisville test), for barometric changes when significant (1.0 inch of mercury caused about 0.2 foot change in observation well), and for river fluctuations (one foot change in river caused 0.40 foot change at a well in the river, 0.10 foot change at the pumped well, and a few hundredths of a foot change 600 feet from the river). Methods of computing corrections do not have an accuracy within limits as close as 0.02 foot. Emphasis should be placed on collection of control data (recorder records of barometric pressure, river elevation, and water-table fluctuations near the test site but outside its zone of influence) so that corrections for these variables can be made. Another variable is the effect of temperature. In the temperature range 40° F to 80° F, a change of 1° F in ground-water temperature changes the viscosity so that the rate of flow is affected about 1.5 per cent. In the second test at Louisville, the river temperature was a few degrees above that of the aquifer. After the first few days the water level in the pumped well had nearly stablized; during the next ten days the flow of warmer water into the aquifer resulted in a slightly higher discharge and at the same time a higher water level in the pumped well. In this case gradients on the river side became less steep as infiltration developed. The best method of handling the temperature variable is to avoid it by conducting the test at a time of year when the river temperature is equal or nearly equal to the ground-water temperature.

In the first test several complications were encountered; free water-table conditions existed on the land side, so that the transmissibility became smaller as dewatering progressed; the lines of wells parallel to the river were under artesian conditions at the start, but the portion near the pumped well changes to a free water table as pumping progressed; a partial barrier of clay restricted flow at the river's edge. Under these field conditions, a great deal of care must be used in reaching conclusions. Steep slopes on the river side may indicate recharge; but they may indicate a partial barrier or very low permeability. Changes in profile slopes with time may indicate changes in the flow-distribution. Flow-distribution changes may result from infiltration; but, on the other hand, may result from temperature changes, or from changes in transmissibility brought about by dewatering of part of the aquifer.

Kazmann's Figure 4 gives the theoretical profiles for pumping an artesian aquifer when a line source is present. Assuming no variation in transmissibility and that pumping has been in progress long enough to establish steady flow, the equation for the drawdown, s_1, at any point a distance r_1 from the pumped well may be written as follows:

$$s_1 = \left\{2.30\ Q \log_{10}[\sqrt{(r_1 \sin\phi)^2 + (2a - r_1 \cos\phi)^2}/r_1]\right\}/2\pi T \quad \ldots\ldots\ldots (1)$$

where a is the distance to the line of recharge; Q, the discharge of wells; T, the transmissibility; and ϕ, the angle between a line from the pumped well perpendicular to the line source and a line connecting the observation well and the pumped well. For the river line of wells, $\phi = 0°$, and

$$s_1 = \left\{2.30\ Q \log_{10}[(2a - r_1)/r]\right\}/2\pi T \quad \ldots\ldots\ldots\ldots\ldots (2)$$

For the land line, $\phi = 180°$, and

$$s_1 = \left\{2.30\ Q \log_{10}[(2a - r_1)/r_1/2\pi T\right\} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

For lines parallel to the river $\phi = 90°$, 270°, and

$$s_1 = [2.30\ Q \log_{10}(\sqrt{4a^2 + r_1^2}/r_1)]/2\pi T. \quad \ldots\ldots\ldots\ldots\ldots (4)$$

By writing (2) for each of two wells on the river side, r_1 and r_2, and dividing, an equation is obtained which is independent of Q and T

$$s_1/s_2 = \left\{\log_{10}[(2a - r_1)/r_1]\right\}/\left\{\log_{10}[(2a - r_2)/r_2]\right\} \quad \ldots\ldots\ldots (5)$$

These equations have been applied to the test data for 68 hours given by Kazmann. Using drawdowns in the river line of wells (S - 1, S - 2), the distance to the line of recharge was computed

by (5) to be 133 feet. Using this figure, values of transmissibility were computed by (2), (3), and (4) based on the drawdown at each well. As no value for discharge is available, transmissibility is expressed as the product of Q and a number (unit: 1/ft). These values shown in Table 2 show that the transmissibility for this aquifer is relatively uniform.

Table 2--Computed transmissibility, Mount Pleasant test

Well no	S - 1	S - 2	N - 1	N - 2	E - 1	E - 2
Transmissibility	0.259 Q	0.259 Q	0.264 Q	0.255 Q	0.246 Q	0.222 Q

Data from the second test at Louisville for five wells on the river line appear below. Three of these wells (R3, R4, and R5) were in the river bed. Drawdowns given occurred after pumping four days at 1100 gallons per minute. Extension of the semi-log plot showing the relationship of drawdown and distance gives a value of about 400 feet for the distance to the line of recharge. Values computed from (5) using pairs of wells give results between 9,000 and 385 feet as shown in Table 3.

Table 3--Computed distance to line source and transmissibility; Louisville test

Well no.	Distance from pump well r	Corrected drawdown s	Computed distance to line source a (from Eq. 5)	Apparent transmissibility T (from Eq. 2)
	ft	ft	ft	gpd/ft
R1	5	6.58		192,000
R2	45	4.40	2000	159,000
R3	101	3.82	9000	124,000
R4	202	2.24	430	116,000
R5	324	0.69	385	117,000

The last column of Table 3 gives computed values of transmissibility using 385 feet as the distance to the line of recharge and assuming in each case that the drawdown of the observation well represents a point on a profile for conditions of uniform transmissibility. The wide deviations show that the assumption of uniform transmissibility is not even approximately valid in this case.

The illustration emphasizes the need for careful planning of a test. In this case, if only three wells had been drilled (R1, R2, and R3), the effective distance to the line source would have been computed as 2000 to 9000 feet instead of 385 to 400 feet. Although part of this difference would have been offset by a larger value of apparent transmissibility, considerable error would have been thrown into final design figures.

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SOME BROAD ASPECTS OF LIMESTONE SOLUTION IN THE TENNESSEE VALLEY

Berlen C. Moneymaker

Abstract--Limestones and other carbonate rocks which underlie approximately 50 per cent of the Tennessee Valley are extensively dissolved. Solution has been in progress a long, but undeterminable, time geologically. Caves, sinks, and other manifestations of bedrock solution abound throughout the region. Deep core borings made in the subsurface exploration of dam sites and large open cuts made at dam construction projects reveal that channels and other solutional openings, some of which are of cavernous dimensions, are present to depths of hundreds of feet below the present water table. In the development of such cavities, geologic structure is of greater importance than the chemical purity of the limestone.

Geologic character of the region--The Tennessee Valley region, embracing the entire region drained by the Tennessee River and its tributaries, has an area of 40,910 sq mi. Nearly half of the total area is underlain by limestone, dolomite, and marble. An additional ten per cent of the valley is underlain by calcareous shale and sandstone which contain members sufficiently soluable to be openly cavernous.

On basis of geology as well as physiography, the Tennessee Valley may be divided into five subregions (see Fig. 1). The salient characteristics of each of these subregions is summarized in the following paragraphs.

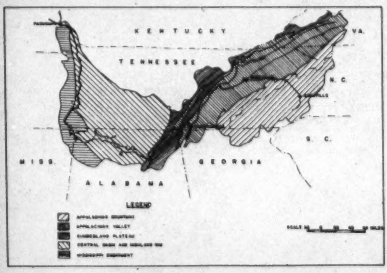

Fig. 1--Geologic subregions of the Tennessee Valley

The Appalachian Mountains are characterized mainly by highly deformed siliceous metamorphic rocks of pre-Cambrian and early Cambrian age and intrusions of late Paleozoic age. Although these rocks consist very largely of gneiss, schist, quartzite, phyllite, slate, and granite, marble occurs in several localities.

In the Appalachian Valley, the rocks are unaltered but highly deformed sedimentary rocks which range in age from early to middle Paleozoic. Limestone and dolomite are the predominant rocks, but calcareous shale is abundantly represented and sandstone and arenaceous shale occur.

The Cumberland Plateau is characterized by unaltered and slightly deformed sandstone and shale of Pennsylvanian age. These rocks are underlain by Mississippian limestone and chert, which are underlain, in turn, by the same rocks that make up the Appalachian Valley. Limestone is exposed in the gorge of the Tennessee River west of Chattanooga and in the channels of tributaries which cut through the plateau-forming sandstones and shales.

The Central Basin and Highland Rim form a subregion characterized by slightly deformed rocks of middle and lower Paleozoic age. All of these rocks are calcareous in character, but they differ widely in the degree of their chemical purity. Massive, pure limestone covers extensive areas but cherty limestone and calcareous shale also have wide distribution.

The Mississippi Embayment is an area of unconsolidated arenaceous and argillaceous sediments, mainly gravel, sand, and clay of upper Cretaceous and Tertiary age. These deposits overlie the slightly deformed Mississippian limestones and other calcareous rocks of middle and lower Paleozoic systems.

Extent of limestone solution--In each of the subregions of the Tennessee Valley the carbonate rocks are extensively dissolved. Soluble rocks not only have been worn down to their present elevation very largely by solution, but they are honeycombed by caves and smaller solution channels to considerable depth.

Some of the largest and most extensive caverns in southeastern United States are developed in the limestones of the Tennessee Valley. Many of the larger caverns, including Indian, Craighead, Cudjo's, Nickajack, and Lookout Mountain have been exhibited as developed attractions and are widely known. Hundreds of other sizable caves occur in the valley and are well known locally.

In addition to the known caves and a few natural tunnels, there are numerous other surface manifestations of bedrock solution in the area. Sinks and sinkhole lakes are common topographic features throughout the limestone terranes and in some localities they give rise to Karst topography (see Fig. 2). In some areas the drainage is entirely underground; in others, surface streams disappear underground only to reappear farther downstream.

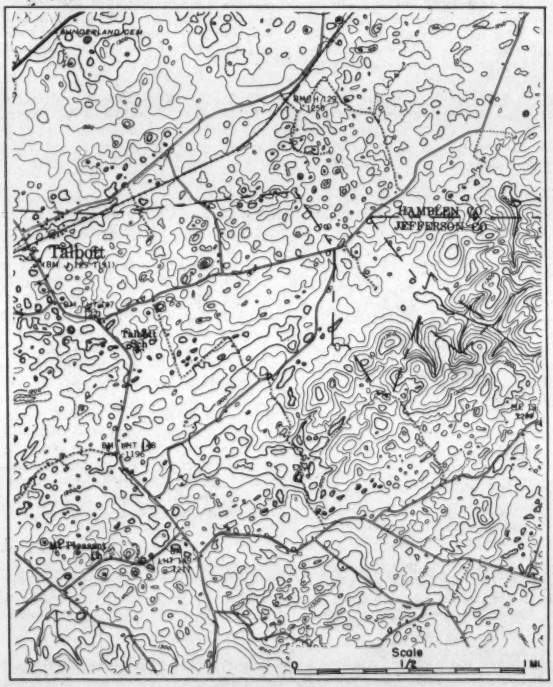

Fig. 2--Karst topography in the Tennessee Valley
(Portion of USGS-TVA Talbott Quadrangle)

The exploration of dam sites by the Tennessee Valley Authority, the United States Army Engineers, and private corporations, the exploration of mineral deposits, and mining operations in the Tennessee Valley reveal that the carbonate rocks are deeply dissolved. At every locality in which carbonate rocks have been penetrated by drill holes, solution cavities have been found to varying depths. In general, these openings are largest and most numerous in the upper portion of

bedrock, becoming smaller and less numerous with increasing depth, but a sizable cavity 1000 feet below the surface was encountered in a zinc mine.

A large majority of the solution cavities encountered at dam sites in the Tennessee Valley are well below the present water table. These cavities vary appreciably in size and shape. The smallest of them are slighly enlarged bedding planes and joints, which represent the initial stage of cavity development. Cavities in more advanced stages of development range up to caverns with cross sectional dimensions of several feet. Some of the caves and channels above the present water table are open; others are filled or partially filled with clay, or mixtures of clay, silt, chert, and stream-rounded pebbles, cobbles, and boulders. Those below the water table, and especially those beneath stream courses, are filled either with water or residual clay and chert, silt, sand, gravel, cobbles, rounded boulders, or varying mixtures of these materials [see "References" at end of paper, MONEYMAKER, 1941].

The most extensive, single solutional feature entirely below the water table to be discovered to date is a large, deep solution channel encountered in the cherty Fort Payne formation at Kentucky Dam [MONEYMAKER and RHOADES, 1945]. This channel is from 70 to 100 feet wide at the top (elevation 270) and narrows with depth, disappearing at elevation 70, a depth of 200 feet below the top of rock. Its entire extension along the strike is not known, but core borings show that it extends more than 1000 feet and afford some evidence that it extends more than 2000 feet. Along the line where it was plugged to insure watertightness of the foundation, it is 70 feet wide at the top and extends downward without any appreciable narrowing to elevation 217, where it bifurcates, the two prongs tapering to extinction at about elevation 70. The channel is developed in a zone of close jointing along the axis of a monoclinal steepening of the dip of the strata on the western limb of a broad flat anticline. The joints, which converge downward, are tensional in origin and stand open, affording free access to ground water. The present channel, which is filled with tightly packed residual chert and clay, was never a large open cavity, but was developed by solution of the rock along a series of steeply inclined joints which were widened to form a series of parallel and nearly vertical channels. Each of these channels was enlarged laterally by the solution of the limestone layers and the subsequent collapse of the intervening chert layers. Lateral enlargement finally brought about the coalescence of the channels and the loss of their individual identities. The continued slumping of residual clay and chert, and the accumulation of sediments derived from the surface, eventually resulted in the plugging of the channel, thus impeding the movement of ground water through its upper portion. Ground water was then able to find an unobstructed channel only at lower levels where lateral enlargement had not progressed far enough to effect plugging. Continued solution again brought about lateral enlargement, resulting in further slumping and plugging, and forcing the ground water to seek new paths at greater depths. Solution, therefore, has occurred progressively at deeper and deeper levels [RHOADES, 1941]. Only the lower part of the channel was found to be sufficiently open to permit the free movement of ground water.

In massive, chert-free limestone and dolomite, most of the larger solution channels are open or at least partly open. At a dam site on the Tennessee River, the cavities were sufficiently large and open to cause the subsidence and even the collapse of the overlying rock under the weight of power shovels. Similar openings of cavernous dimensions were encountered in the excavations at several other dam sites.

Relation of solution to geologic structure--Bedrock solution is controlled rigidly by the geologic structure. In the Tennessee Valley the structure is of much greater importance than the chemical purity of the rock. The extensively jointed Fort Payne formation, which is 33 per cent chert in the vicinity of Kentucky Dam, is much more cavernous than the less jointed pure limestone formations a few miles away; the highly deformed impure argillaceous members of the Chickamauga limestone at Chickamauga Dam are much more extensively dissolved than the flat-lying pure limestone members a hundred feet away. Solution is initiated along joints, bedding planes, unconformities, faults, and the crests of anticlines, and in its early stages the resulting cavities are narrow openings along these structures. As solution progresses, enlarging the cavities, the structural control commonly becomes less obvious, and continued cavern development may result in the complete loss of evidence of the structural control.

Age of solution cavities in the Tennessee Valley--The cavities and caverns in the Tennessee Valley are developed in rocks ranging in age from pre-Cambrian (Murphy marble) to Mississippian (Bangor limestone). In most cases it is impossible to date any stage in the development of existing solutional openings, whether large or small. In one case fossil remains are helpful; in another the sediments deposited as cave-filling afford a clue.

Craighead Caverns is one of the largest caves in the Tennessee Valley. In 1939 and 1940, the bones and footprints of Pleistocene felines were discovered in a narrow passage of this cave [SIMPSON, 1941]. As the cave was above the water table and sufficiently dry to be occupied by animals in the Pleistocene, it is unlikely that it has been appreciably enlarged since that time. The history of this large cave probably dates from the Oligocene, or even Eocene, but evidence, positive or negative, is entirely lacking.

The deep solution channel at Kentucky Dam contains pockets and stringers of a fine-grained, micaceous sand, which has been identified as Ripley [RHOADES, 1941]. Although the Ripley sand is not present at Kentucky Dam, remnants of the formation are present on the adjoining highlands, and undoubtedly it once covered the entire area.

In late Pliocene or early Pleistocene time, the Tennessee River cut a deep valley, now partially refilled with alluvium, in the lower reaches of its course. This erosion removed the Ripley sand from the immediate area. The sand, therfore, was introduced into the channel from the surface prior to this time. The lowest unslumped deposit of Ripley sand in the channel is at elevation 200, and solution must have progressed to this elevation, or even lower, by late Pliocene or early Pleistocene time. As this elevation is about 245 feet below the former base of the Ripley sand, solution probably was inaugurated not later than the Miocene and may have started as early as late Lower Cretaceous time.

Conclusions--On basis of studies and observations covering more than a decade, the following conclusions may be drawn in regard to the solution of limestones in the Tennessee Valley: (1) The limestone and related carbonate rocks are extensively and deeply dissolved. (2) Although pure carbonate rocks are more soluble than argillaceous and cherty limestones, the latter are extensively dissolved where the geologic structures are such as to facilitate the free ingress of ground waters. (3) The geologic structure is of somewhat greater importance than chemical purity, per se, as a factor in the solution of limestones and the formation of caverns and smaller solutional openings. (4) The limestones of the Tennessee Valley have been undergoing solution for a long time, geologically. Some of the larger caverns and channels may date from late Mesozoic time.

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GROWTH OF THE GHYBEN-HERZBERG TRANSITION ZONE UNDER A RINSING HYPOTHESIS

Chester K. Wentworth

According to the Ghyben-Herzberg principle, fresh water overlies salt water within the meshwork of a permeable rock structure. Under perfectly static conditions of balance the only mechanism for interpenetration would be diffusion. The method of setting up graded densities for mineral separation has been used by mineralogists. In it, a lighter grade of some heavy liquid is placed carefully above a heavier grade which is miscible with it. After some hours, interpenetration by diffusion takes place so that the sharp boundary is replaced by a graded one, in which several minerals of known densities in the proper range will stand at the several appropriate levels, and thus permit the calibration of the density gradient.

In the case of fresh and salt water the same process would probably take place but there is reason to think that the process of diffusion is overrun by actual mixing, particularly because of the occurrence of larger channels and openings in the meshwork. Let us approach the simple matter of moving a sharp boundary through the rock because one side or the other received added pressure. Let us assume that such movement takes place by successive jumps or unit distances. It is immaterial for this discussion whether these be feet, meters, or rods. As water of one kind, say fresh, moves by a distance of one unit, into a new unit space, we assume that its displacement of the water already in such space is incomplete, because of wall adhesion, and smallness of openings and recurved, blind openings. Let us assume that after one unit movement the resulting water in a unit space consists of 90 per cent invading water and 10 per cent residual water. Any other small percentage of residue would equally well serve our theory. In the case in point the fresh water becomes contaminated with ten per cent of salt water. Now if another unit of movement takes place the water in the new unit invaded becomes 81 per cent fresh water and 19 per cent salt water and the water in the unit just left by the 90 per cent fresh water becomes 99 per cent fresh, because of having been rinsed twice on a ten per cent residue basis. This concept of rinsing follows an exponential law and is well known to chemists, who thus reason that rinsing with a given total amount of water is most effective if the water is used in a large number of small portions instead of only one or two larger portions.

The accompanying diagram is an arithmetic model showing how such a rinsing process might work (see Fig. 1). It carries the process through one complete cycle of ten units of downward

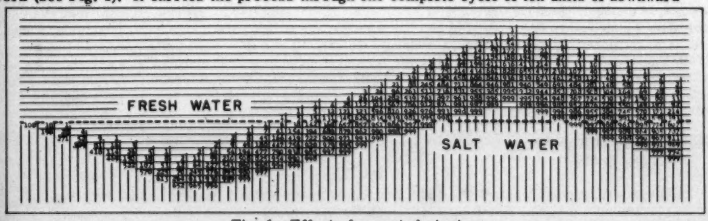

Fig. 1--Effect of repeated rinsing

movement toward salt water, then ten units of return and ten units beyond the initial line and finally ten units back to the original neutral position. The proportions of salt water in parts per thousand are shown by the figures in each compartment; the vertical lines show salt water, or 1000 parts per thousand and the horizontal lines show fresh water or 0 parts per thousand. Because of rounding to the nearest thousandth, there is a slight raggedness on the edges at some points but the general behavior is well shown. On the first advance, the frontal percentage of fresh water is quickly cut down (arithmetic complement of the figures) and the salt proportion rises to give bluntness to the advancing front, with the 500-part line just back of the first compartment after stage 7. Very

quickly after reversal the margin on the salt water side becomes more gradual and the 500-part line moves out into the middle. At stage 30, where the salt water has reached its highest position, the mid line is somewhat above the middle, but at the final stage the transition zone has become symmetrical, with the successive numbers almost exactly balanced with reference to 0 or 1000, as the two sides require. Plotting these values gives a striking sigmoid transition curve with maximum slope at 500 and with the ends asympotic to the values 0 and 1000.

From this experiment and a few other supplementary to it, it is seen that under this hypothesis the transition zone becomes wider as the fresh-salt boundary moves in either direction. The transition zone tends to become symmetrical when cycles of alternation are completed, and probably eventually after any complete series of migrations. The width of the transition zone probably approaches a stable value for any given amplitude of migrations, but is subject to increase if migrations advance to new amplitudes. As the width of the zone increases the changes of composition at the margin are more gradual; the edge is more thinly wedge-shaped.

The reader should remember that this is a simplified model concept; it is fully recognized that at no single place would just these smooth conditions prevail. There are larger openings leading from salt to fresh and from fresh to salt water and under alternating reversals of potential, there will in any natural aquifer be filaments of water of each kind invading the realm of the other. Yet it is conceived that just these movements of alternate invasion, both by filaments and by more orderly mass movement, must be integrated into a transitional pattern closely approximating that developed in this application of rinsing theory.

If we accept it in principle, light is thrown on several observed phenomena. In most Ghyben-Herzberg systems, artificial draft aggravates indraft of salt water, even if not at all points or in shallower wells. This is natural since artificial draft undoubtedly increases the range and amplitude of migration of the salt-fresh boundary. Further, in areas where development has taken place, a common discussion is centered around the question whether after heavy draft and rise of the boundary as the Ghyben-Herzberg lens shrinks, the water will become as free from salt as formerly if the head of the upper part of the lens is restored and the boundary at the bottom has been depressed to the former position. Some have insisted on complete reversibility; others have asserted that salt water would be trapped and would remain as a residual saline contamination.

If we accept the results of this rinsing theory, that the transition zone becomes wider, we see that even if the center of the zone of transition is depressed to a former position, corresponding to the former head of fresh water, the upper fringe of the zone, now wider, may remain higher than its former position, to any specified limit of salinity. In the practical use of water, we are interested, not in the mid-position, or water of 50-50 composition, but in water carrying an admixture of not over one or two per cent of sea water at the most. Hence our interest centers on the position of the thin upper fringe of the zone. Thus it appears that in a sense both parties to the discussion are right. Restoration of the middle of the transition zone may with sufficient increase of head be completed and this may be interpreted as reversibility of the process. But in practice, because of the widening caused by movement, presumably on a greater amplitude than before, the upper fringe has expanded and the water at the bottom of a given well, unhappily, may remain much more saline than before. Perhaps we can say the process is reversible as to the middle line of equivalent balance, but that the former condition is not confidently restorable as to low salt content in a given well which may now find itself reaching the widened diffusion zone. Thus we seem to have a resolution of this somewhat common speculation, as well as a basis of explanation of some other characteristics of the transition zone.

Honolulu Board of Water Supply,
Honolulu, Hawaii

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Transactions, American Geophysical Union Volume 29, Number 1 February 1948

THE ANCIENT EUROPEAN BASEMENT BLOCKS--Preliminary Note

Hans Cloos

The major tectonic features of our continents are generally supposed to be younger than the deformed rocks which they transgress. During the last two or three decades observations began to accumulate which prove that several, if not all, of the main fractures or fracture zones in Europe are old and have been active practically during all the tectogenetic periods of the Earth's history. This indicates that the Earth's crust was divided into polygonal fields or blocks of considerable depth or thickness during an early stage of its history. In the following, the author will speak of "basement blocks" which are separated by "geofractures" or "geosutures." Since the geanticlines are of later origin they are profoundly influenced by the shape and behavior of the respective basement blocks.

The author's own contributions to this problem date back to 1910, when he first investigated the influence of old Tertiary faults on younger Tertiary folds in the Swiss Jura mountains near Basel [see "References" at end of paper, H. CLOOS, 1910]. Later on he dealt with the Rhinegraben, the primary boundary of the Rhenish Schiefergebirge, the pre-Cambrian stages of important block boundaries in Norway and Sweden, with the old structures in Silesia and the Bohemian mass, the Harz Mountains, northeast and South Africa, certain areas in North America, the Atlantic structure in the Azores, and with the Red Sea. Among the many important observations of others in different countries, F. Dixey's discovery of an older Nyassa fault trough in Africa is the last but not the least. SONDER [1938], in his papers on Europe and Central America, tried to construct a pattern by drawing straight lines in different directions.

A few years ago the author demonstrated the fact that an active geofracture can even "underpass" an active syncline: the Paleozoic folds in Germany are crossed obliquely by two straight zones of primary axial depression. The major boundaries of the stratigraphic facies coincide with the depression (see Fig. 1). This means that the geosyncline developed above a foundation of heterogeneous fields or blocks.

A second example of a somewhat different character is the so-called North-South zone in Silesia shown in Figure 2 [H. CLOOS, 1922]. This zone was active frequently in early Paleozoic, Mesozoic, and Tertiary times. It deflected the northwest trending folds into a meridional direction. It gave rise to five plutons of differing ages and compositions. Four of these are inserted intimately between the bent folds. The same zone served as locus for one Permian and one Cretaceous fault trough both of which are sickle-shaped like the older pluton and conformably intercalated into the surrounding structures.

All three major geofractures show a remarkable parallelism in a nearly meridional north-northeast-southsouthwest direction. Several others show the same general trend and turn out to be ancient as well as deeply rooted: The Silesian zone continues southward along the east end of the Alps and influences their trend as it does the Paleozoic trends farther north. The primary axial depression in the Rhine area continues southward into the famous Rhine graben and its Paleozoic predecessor. To the north this depression continues into the pre-Cambrian and Paleozoic fractures of Norway and Sweden. The pre-Cambrian stages of the later faults were described by Bederke in connection with the mapping of the Swedish Geological Survey near the Vettern-lake. Stille dates these fractures as not older than the consolidation of the surroundings; that is, Permian in Scandinavia and more recent in Central Europe.

Additional comparable structures which are shown in Figure 3 together with other megastructures of Europe, are: The meridional fault troughs of the Plateau Centrale and the Rhone valley; the suboceanic depression off the western shore of Norway (Fig. 3, 3) which limits the Bergen arcs and disperses their strike; the north-south zone between Ireland and Scotland (Fig. 3, 1) with its strange horizontal flexures and the famous old Tertiary plutovolcanoes [RICHEY, 1939]. The Malvern line in southern England (Fig. 3, 5) can perhaps be considered as a less prominent zone of similar character. In its exact northern extension the Shetland Islands exhibit another example of sharp horizontal flexure into a meridional (Fig. 3, 2). Some other and minor zones can probably be distinguished in the southeastern portion of the continent.

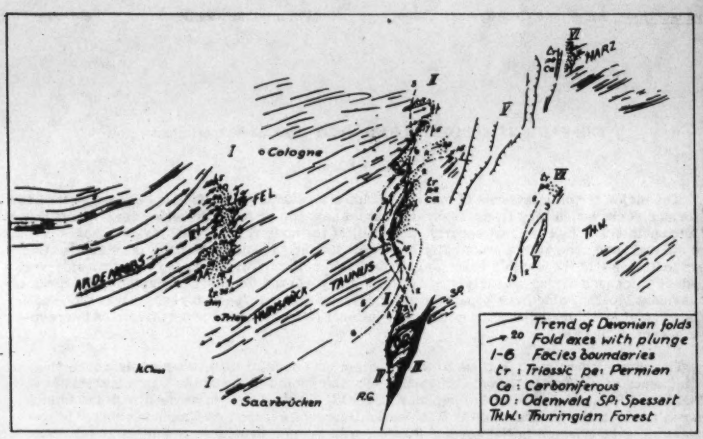

Fig. 1--The western Variscan folds in Central Europe; wavy lines of average meridional strike: boundaries between the lower Devonian and younger folded sediments (middle and upper Devonian, Carboniferous stippled); I-I: North-south zone of the Eifel, folded middle Devonian between two axial flexures, unconformably covered by lower Triassic (tr) sandstones which dip gently towards the center; II-II: Eastern slope of the "Rheinische Schiefergebirge," folded Devonian and lower Carboniferous pitching steeply eastward and covered by upper Permian and Triassic dipping gently eastward; lines 1-6 indicate (personal communication by W. Kegel) major facies limits within the (1) Ordivicium and Gotlandium, (2) Gédinnien (lower Devonian), (3) Siegen series of the lower Devonian (during 2 and 3 the space between the western and eastern limits received no sediments at all), (4)-(6) Higher horizons of the lower Devonian; the area east of the facies limit received thin calcareous sedimentation, the western area subsided under a mighty sequence of marine shales and sands; III: Palaeozoic (and older?) deformations and intrusions along the extension of the Tertiary Rhine graben (R. G.); IV: Young (Tertiary) along the western slope of the Odenwald (OD); Spessart (SP); V: Late faults within the main meridional fractured zone: VI: Folded Carboniferous at the NW corner of the Harz Mountain, covered by lower Permian and Triassic; VII: Lower Permian on the western slope of the Thuringian Forest (Th. W.)

A different system of ancient geofractures trends northwest-southeast through the central and Mediterranean part of Europe. Great age and frequent activity can be proven for most of the central European examples. The northeastern margin of the Harz Mountains and the "Pfahl" in the Bavarian-Bohemian forests are best known. Close relation between Paleozoic plutonic activity and Tertiary faulting has been proven for the latter [CLOOS, BALK, and others, 1927].

The basement blocks which are bounded by the above mentioned geofractures must, of course, be as old as the fractures. The blocks show a remarkable meridional elongation and very similar dimensions. Their breadth varies between 300 and 500 km in an east-westerly direction.

As areas of different horizontal and vertical displacements these thick and permanent blocks must have influenced the sedimentation on their upper, and the magmatic evolution on their under surface. Their effect on the structural evolution of the corresponding geosynclines and geanticlines can be expected to be intense. The relation between younger folds and the configuration of the blocks is very intimate. They vary with the direction of folding movement in relation to the block boundaries. Longitudinal ranges are usually straight as in Italy, Greece, and the Pyrenees. Transverse ranges appear suspended between marginal sutures and are formed as sigmoidal festoons or as garlands. The Alps are composed of a northern "sigma" and a southern garland,

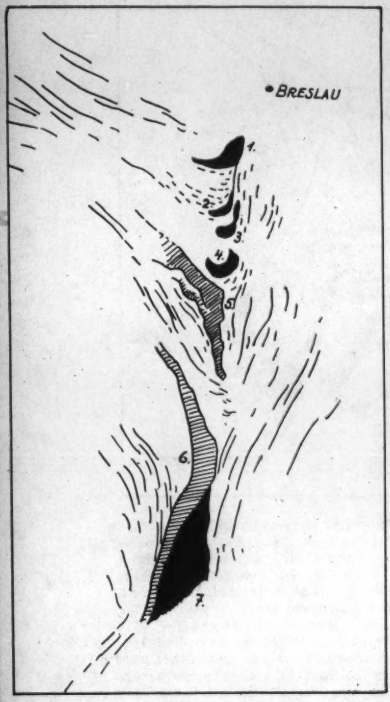

Fig. 2--The north-south zone in Silesia; long lines: Trend of the folded Palaeozoic (and older?) sediments and crystalline schists; (1) the serpentine pluton of Mount Zobten; (2) "syenit" of Nimptsch; (3) serpentine pluton of Frankenstein (with the well known nickel mines); (4) the "syenite" of Glatz-Reichenstein; (5) the Cretaceous fault-trough of the Neisse valley; (6) the Permian depression of Boskowitz; (7) the Palaeozoic pluton of Brünn (Brno) in Czechoslovakia

both suspended between the Rhine-Rhone geofracture in the west and the extension of the Silesian north-south zone in the east. The major features of the Caledonian and Variscan ranges in Europe can be also interpreted as limited by pre-existing blocks. Some of the major structural lines in the interior of Scotland could be related to a slight torsional deformation of the block which is limited by the two geosutures mentioned above. Recent experiments by the author have shown that minute shear of supporting blocks results in considerable secondary displacements in the cover.

Many attempts have been made (Ed. Suess, Termier, R. Staub, Kober, Argand, Stille) to connect the Mediterranean folds to endless arcs. The results of those efforts indicate that the relations are uncertain. In some cases facts had to be neglected or even falsified in favor of an artificial connection. Only the oldest of these constructions (Ed. Suess, 1885) accepted the characteristic southward curvature at the eastern end of the Balearic arc between Spain and Italy. All other concepts bend it to the wrong side for the sake of better connection with some northern folds. Such corrections of nature may be replaced by reference of the folded arcs to their older and local conditions as represented in the constitution of the lower crust.

Similar meridional articulation seems to prevail in North America and the form and trend of older and younger folds appears determined by the outlines of basement blocks. The dimensions are larger, however, within the larger continental unit (average 800 km). Under the Atlantic Ocean, the blocks are broader and the geosutures prefer other non-meridional trends [H. CLOOS, 1937]. The continental slopes are the first structural units whose effect on later geosynclines and geanticlines has been recognized and discussed. These large zones, may, however, be fundamentally different from continental or oceanic geofractures.

The deformation of the Earth's crust and the major features of its surface history can be easier and better understood if the visible structures are not directly connected with supposed underground forces like subcrustal connection currents, but if we introduce an anisotropic and inhomogeneous aggregate of older units which support the surface materials and serve as loci of attack, as levers, and as conductors for the forces of the deeper underground.

As generally known, deep-focus earthquakes have recently been discovered. Since such foci may be related to lines or planes of major tectonic significance, they seem to confirm the concept of deep and old crustal blocks and sutures as derived above from the wide net of ancient structures at the surface.

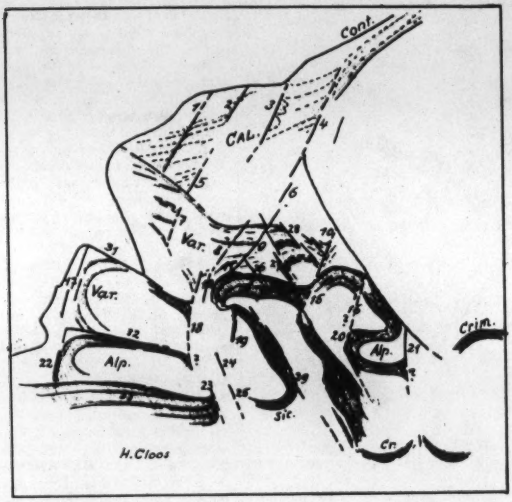

Fig. 3--Preliminary map of some basement blocks and major geosutures in Europe; Cont., Continental slope; Cal., Caledonian ranges; Var., Variscan ranges; Alp., Alpine ranges; Sic., Sicily; Cr., Crete; Crim., Crimean-Caucasus Range: (1) N-S zone between Ireland and Scotland; (2) Shetland flexure; (3) depression off the shore of southern Norway (cutting off the Bergens arcs); (4) Oslo fractures and their hypothetical northern extension; (5) Malvern line; (6) N-S fractures in the basement of northwestern Germany (and Denmark?); (7) fractures and dikes near the west coast of the Cotentin peninsula; (8) the N-S zone of the Eifel; (9) the main geofracture between the Rhenish Schiefergebirge and the Harz; (10) the Silesian N-S zone; (11) the Rhine graben; (12) the faults and fault-troughs near and west of the Rhone valley; (13) the tectonic boundary between the western and eastern Alps (axial syncline along the Rhine valley); (14) the Judicarien line in the southern Alps; (15) the hypothetical southern prolongation of the Silesian N-S zone; (16) the limiting faults at the eastern end of the Tatra Mountains; (17) fractures terminating the Iberian Peninsula; (18) an hypothetical southern continuation of the fractures of southern France terminating the Pyrenees and the Balleares at their eastern ends; (19) the line of Corsica; (20) the straight meridional western limit of the Carpathians; (21) the earthquake line forming the western limit of the Dobruja and possibly terminating the Balkan-ranges; (22) minor breaks west of the Gibraltar arc; (23)-(25) hypothetical fractures between the eastern Atlas and Sicily; (24) the Campidan-graben on Sardinia; (25) the Pantellaria line; (26) the Kaiserstuhl-Bodensee fractures in the Black Forest; (27) the echelon system of fractures along the western slope of the Bohemian mass; (28) the same on its eastern side (Silesia); (29) and (30) longitudinal axes of Italy and Greece; (31) southern slope of the Biscaya Gulf; (32) Guadalquivir fault in southern Spain; (33) Atlas

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MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY FROM JULY 1, 1946 TO JUNE 30, 1947

Elliott B. Roberts

The close cooperation maintained in former years with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington was continued by temporary loans of certain instruments and by exchange of data.

Magnetic surveys

United States and Alaska--A regular repeat field party was in operation in central and northern Alaska. As usual, a number of observations of magnetic declination were made by parties of the Survey which were not engaged primarily in magnetic work. These included observations made at several airports in the United States, and in connection with hydrographic surveys along the coasts of the United States and Alaska.

Other American republics--The program of magnetic repeat observations in other American republics, which was begun in November 1941, continues. This work is being executed in cooperation with the Interdepartmental Committee on Scientific and Cultural Cooperation, United States Department of State. The work of the sixth season, February to June 1947, included magnetic observations in seven American countries; namely: Ecuador, Bolivia, Peru, Chile, Argentina, Uruguay and Brazil.

Arctic--Special magnetic projects were undertaken in the Arctic and Antarctic. Magnetic observations were made at eight stations near the north geomagnetic pole by Joel B. Campbell, Geophysicist of the United States Coast and Geodetic Survey, in connection with the Expedition Nanook of the United States Navy. One station was at Thule, Greenland, and the others were on Devon Island and neighboring islands in Canada.

The training of a Canadian observer was begun for another Arctic magnetic survey.

Antarctic--In connection with the Navy Antarctic Expedition, Charles A. Schoene and H. H. Howe made extended magnetic observations at Little America IV. In addition, advantage was taken of the opportunity to observe at Old Panama (Panama) and at Amberly, Christchurch (New Zealand). Several Navy observers who participated in this expedition received preliminary training by the Coast and Geodetic Survey.

An observer was trained for, and instruments loaned to, the Finn Ronne Antarctic Expedition.

Distribution of observations--The distribution of magnetic observations from July 1, 1946 to June 30, 1947 is shown in Table 1.

Work in the office

Furnishing data--As in previous years, magnetic data were furnished to nearly every agency of the Government which was engaged in making maps. The three-hour-range indices, K, were furnished daily to the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and to several Governmental agencies, and a weekly report on magnetic conditions (Cheltenham K-indices) was instituted in January. Magnetic data were furnished daily to the National Bureau of Standards in connection with its program of forecasting radio-transmission conditions. Many inquiries were answered, providing specific data in most cases.

Central depository for magnetic data--An intensification and expansion of the work of collecting and maintaining observational material from world-wide sources has been begun, and is formally reflected in the new organic act outlining the functions of the Bureau [see 80 USC 373, Sec. 3].

Table 1--Distribution of magnetic observations from July 1, 1946 to June 30, 1947

State or region	Repeat stations				Other stations	Totals
	New		Old			
	Complete	D only	Complete	D only		
California	...	...	...	...	1	1
Indiana	...	...	...	...	1	1
Tennessee	...	...	...	1	...	1
Vermont	...	...	...	...	1	1
Virginia	...	...	...	...	2	2
Washington	...	...	...	...	2	2
Alaska	7	...	5	...	11	23
Canada	...	...	...	...	7	7
Greenland	...	...	...	...	1	1
Panama	...	...	1	...	...	1
Argentina	...	...	1	...	...	1
Bolivia	...	...	3	...	...	3
Brazil	...	...	7	...	...	7
Chile	...	...	3	...	...	3
Ecuador	...	...	1	...	1	2
Peru	...	...	1	...	...	1
Uruguay	...	...	1	...	...	1
Antarctica	1	...	...	...	1	2
New Zealand	...	...	1	...	...	1
Total	8	...	24	1	28	61

Work on charts--The isogonic chart of the United States for 1945, which was issued in June 1946, marks the inception of a new procedure in the construction of such charts. Briefly, the observations were plotted as "anomalies" or departures from a highly smoothed datum chart, and then used to draw isanomalic lines which largely suppress the minor fine-scale structure and reflect primarily those departures which prevail over appreciable local areas. These isanomalic patterns are then compounded with the datum chart to produce the final isogonic chart. The procedure is discussed in some detail in the publication "Magnetic Declination in the United States, 1945" [see below, Serial 664], and a preliminary outline of it was presented in the Transactions in 1942 [pp. 294-296]. The isanomalic patterns have also proved useful in furnishing data for nautical charts along the United States coasts, thereby helping to attain suitable recognition of local conditions. As in past years, current revisions of compass data were accomplished with respect to several hundred nautical and aeronautical charts issued or revised during the year.

Work on publications--The scaling of the mean values for each hour at the magnetic observatories has been suspended. Beginning in 1946, only the values for the 24th hour of each day are being regularly scaled. Approximate monthly and annual values are derived from the abridged scalings. The new procedure will be important in affording more nearly up-to-date information at all times.

The first number of a new and trial form of report [MG-report] was issued, entitled "Cheltenham Magnetograms, January to June 1946 [No. MG-C46.1]. It contains quarter-size reproductions of the magnetograms for the first six months of 1946, together with approximate monthly and annual mean values derived from the abridged scalings discussed above. If adopted finally, the new form of report will supersede for all United States Coast and Geodetic Survey observatories the series of biennial volumes heretofore issued containing numerical results.

The MG-report for Sitka for the same period is in press.

Processed report MO-24, "Magnetic Observatory Results at San Juan, Puerto Rico, for 1929-1930," was issued, and the similar report of Honolulu results for 1937-1938 is in press.

Serial 677, "Magnetic Observations in the American Republics, 1941-1944," was issued, and Serial 664, "Magnetic Declination in the United States in 1945," is in press. Serial 166, "Directions for Magnetic Measurements," was reprinted with a few slight corrections.

Observatories

Four of the regularly operated observatories continued in operation without serious interruptions. At Honolulu the magnetograph was transferred to a new site, and a contract was awarded for the construction of an observatory near Fairbanks, Alaska.

Cheltenham, Maryland--Routine operation of three magnetographs continued. The scale values of the variometers are approximately as those shown in Table 2. The Adie instruments are equipped with eye-reading scales.

Table 2--Scale values of variometers at Cheltenham

Variometers	D	H	Z
	'/mm	γ/mm	γ/mm
Eschenhagen	1	2.7	4
Adie	1.1	4	12
La Cour	4	30	..

Field instruments of the United States Coast and Geodetic Survey and of other agencies were standardized at Cheltenham. The Department of Terrestrial Magnetism of the Carnegie Institution of Washington cooperated in maintaining the international magnetic standards.

College, Alaska--A contract was awarded for the construction of a new observatory near Fairbanks, Alaska. It will be built on the grounds of the University of Alaska, College, Alaska.

Honolulu, Territory of Hawaii--In March 1947, the magnetograph was transferred to the new observatory a few miles distant. This completed the transfer of the observatory, which was necessitated by excessive vibration transmitted from low-flying aircraft. The old site was directly in line with a heavily used runway.

San Juan, Perto Rico--Routine operation of the magnetograph continued throughout the year.

Sitka, Alaska--Two magnetographs (sensitive and insensitive) were maintained in operation.

Tucson, Arizona--Normal operation of the magnetic observatory and cooperative work with the Department of Terrestrial Magnetism, Carnegie Institution of Washington, on atmospheric potential-gradient and positive and negative air-conductivity were continued.

Instrumental program

The making of instruments for geomagnetic work is a highly specialized activity, heretofore confined chiefly to a very few European firms. During the past year, however, domestic makers have contracted to build several variometers for the recording of magnetic fluctuations, using new designs which embody certain modifications worked out by the Survey. In addition, two large Earth inductors of unique design have been received.

The automatic declination recording station at Gatlinburg, Tennessee, was reactivated in July. Active steps have been taken toward the establishment of two similar stations, one in northern Florida and one at Logan, Utah.

Improved three-component tape recorders for use at secondary magnetic observatories are nearing completion.

Some progress has been made on the development of a pen-recording magnetograph for use in the Arctic.

Assistance was given the War and Navy Departments in the instrumental aspects of various magnetic projects.

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Washington 25, D. C.

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MODEL STUDIES MADE AT THE UNIVERSITY OF CALIFORNIA RIVER AND HARBOR LABORATORY

J. W. Johnson

Abstract--Since establishment of the River and Harbor Hydraulic Laboratory at the University of California at Berkeley, approximately ten years ago, numerous model studies have been made in connection with a variety of engineering problems. Many of the data obtained in the various model studies have not been published previously. Since many of the results may be of interest to other investigators, both because of general principles of application as well as the limitations of the models, a few of the more important investigations are described briefly.

Columbia River Estuary--The first investigation at the laboratory, made for the Pacific Division of the Corps of Engineers, included an analysis of certain field data and a model study of the estuary of the Columbia River in which means of straightening and maintaining navigable channels were tested. In the model, built to scales of 1:3600 horizontal and 1:128 vertical, only that portion of the estuary between the ends of the jetties and Three Tree Point was under investigation (see Fig. 1). The upper river was reproduced in "labyrinth" form only for the purpose of obtaining the correct tidal prism and the proper phase relationship between time of tide and time of current. A complete discussion of the quantitative relationships governing the design and operation of estuary models has been published elsewhere [see "References" at end of paper, O'BRIEN, 1935].

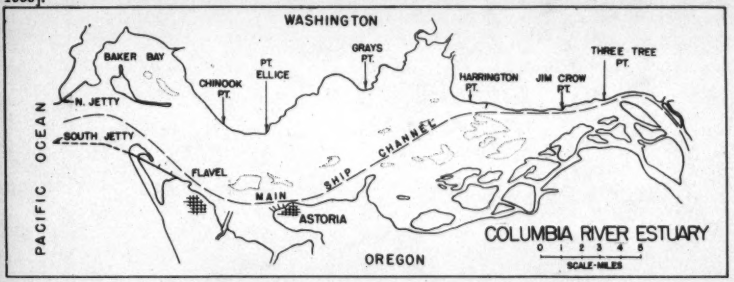

Fig. 1--Area covered in Columbia River Estuary model

The model was built originally for the purpose of studying the methods of operating tidal models, and particularly to determine the necessary size of a model of the Estuary of the Columbia River It was of the movable-bed type, but, perhaps owing to the relatively large distortion (distortion-64), it did not reproduce the existing estuary channels. Whether this result indicated a real disagreement between model and nature is questionable since the estuary itself may again cut a channel, as it appears to have done in the past, similar to those observed in the model. The model appeared definitely to be too small and too greatly distorted for a study involving bed-load transportation, and it was abandoned in favor of a fixed-bed model in which the tendency towards scour or fill was inferred from the changes in velocity produced by dredging, training works, and other work.

The comparison of nature and model data on currents showed sufficiently good agreement that model data was taken as representative of average conditions, particularly as regards direction of current. By taking vertical photographs of confetti floating on the water surface, mosaics covering the entire Estuary at ten instants during the tidal cycle were made for both normal and freshet flow conditions in the river. Comparisons of current velocities and directions with and without channel correction works were then made, in which it was assumed that since the model agreed with nature when the model bed was molded to conform to nature at the time of the current surveys, it would exhibit equally good correspondence with any modified conditions.

In addition to the model study, laboratory investigations were made on the transportation of sand in pipe lines [O'BRIEN and FOLSON, 1937] and the transportation of Columbia River sand by flowing water [O'BRIEN and RINDLAUB, 1934]. Field observations included measurements on the transportation of sand by wind [O'BRIEN and RINDLAUB, 1936] and surveys of currents and salinity in the Estuary. Because the data are too numerous to summarize in this paper, a complete list of unpublished reports on the model study of the mouth of the Columbia River is given in "References" [TECH. MEMO., Nos. 1-5, and 7-21].

Breakwater and beach erosion studies at Santa Barbara--The purpose of these studies was to test the reliability of relatively small scale models for sand movement and beach erosion. The method used was to construct models of portions of a shore line and compare the model results as obtained by varied conditions of littoral drift and wave action with known results in nature. The first model in this series of investigations was of the Santa Barbara breakwater, where the problem was concerned with the accretion of sand in the harbor [LAPSLEY, 1937; and LILLEVANG and BRANT, 1937]. At this point on the coast, between 800 to 1000 cu yd of sand per day had been estimated to be working generally southeastward under the force of the littoral currents caused by wave action. Figure 2 shows the nature and extent of the sand fill subsequent to the construction of the breakwater. The breakwater was first constructed in 1929 with a gap left at A (see Fig. 3),

Fig. 2--Aerial photograph of Santa Barbara Harbor, June 15, 1944; note sand deposit inside the breakwater tip and against the shore end

with the expectation that the sand would pass through the harbor and continue southeastward along the shore line. Instead of continuing through the harbor and down along the coast, however, the sand formed a shoal in the harbor. That such a condition might be expected to occur is illustrated by Figure 3, which shows a refraction diagram for waves approaching from the west (the prevail- wave direction for this locality). Thus, the littoral current which transports sand is produced by the angularity at which the waves break on the beach, but it is noted that inside the harbor the

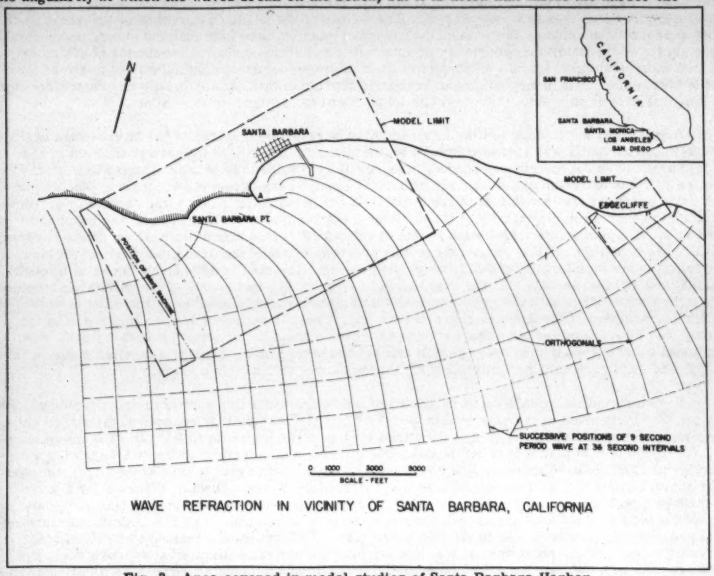

Fig. 3--Area covered in model studies of Santa Barbara Harbor and groins at Edgecliffe

waves are traveling in a direction opposed to that of the waves west of the breakwater. The opposing currents within the harbor, therefore, induce deposition. The orthogonal lines in Figure 3 are shown to give an indication of the variation in wave height along the shore resulting from refraction of the waves; thus the ratio of the wave height at a particular point near shore to the height in deep water is equal to the square root of the ratio of the distance between two adjacent orthogonal lines at the point in shallow water and the distance between the same orthogonals in deep water.

Within a year after construction of the Santa Barbara breakwater, the shoal inside the harbor increased so rapidly that it was necessary to close the gap (at A, Fig. 3) in order to prevent the harbor from filling to the extent that it would be useless without dredging. After closure of the gap, the littoral drift accumulated against the shore arm of the breakwater, but by 1934 the sand fill had so increased in volume that the sand worked along the breakwater, around the tip, and into the harbor (see Fig. 2).

The model for studying deposition in the vicinity of the breakwater was built to a horizontal scale of 1:750, a vertical scale of 1:100, and was approximately 20 feet by 12 feet in plan. Since the problem under investigation did not concern scour, but only littoral drift, the model bed was of the fixed-bed type in which a sand load equivalent to 1000 cu yd of sand per day in nature was introduced at Pt. Santa Barbara and allowed to move eastward along the coast. Waves were generated by a wave machine located as shown in Figure 3. Locating the wave machine in this position gave a wave front in the vicinity of the breakwater similar to that shown by the refraction

diagram which was prepared for a nine-second wave (the average observed in nature) approaching from the west in deep water. The model was operated both with and without tide effects.

The result of this investigation was that the model reproduced, in general, every major change in nature. The shoal inside the breakwater was formed when the gap at A (see Fig. 3) was left open. When the gap was closed, sand filled against the breakwater and worked along the sea arm of the breakwater and into the harbor. It did not, however, work back along the inside of the breakwater as observed in nature (see Fig. 2). The details of the fill and the rate of progression were not reproduced accurately in the model. The correlation of time in model and nature failed completely; however, this fact does not impose serious limitations upon the usefulness of the model, for in most such problems the ultimate result is of more importance than the time required for it to take place. It is of importance to recognize that observations on a prototype are seldom complete, and even if complete, they would be impractical to incorporate in a model.

Because the construction of the Santa Barbara breakwater resulted in the interception of the sand which normally was moved eastward by the littoral current, the beaches to the east of the breakwater have been seriously eroded. The result is that the only beaches found within five miles of the breakwater to the east are relatively small areas preserved by groins. The action of these groins is similar to that of the Santa Barbara breakwater, that is, the sand is intercepted and forms a beach in the vicinity of the structure, but serious erosion occurs on the beaches to the east. A typical groin installation is that at Edgecliffe, three miles southeast of Santa Barbara, where the construction of two concrete groins preserved part of the beach, but serious erosion resulted to beaches further east. These groins were constructed in 1924 and increased in length to 200 and 260 feet in 1929. At the shore ends, they were 175 feet apart. Even with these lengths, sufficient material passed the groins to maintain relatively stable beaches to the east; however, after construction of the Santa Barbara breakwater, when the supply of sand to this reach of the coast was intercepted, erosion started on the beaches beyond the groins. By 1935 all sand was stripped away except immediately west of and between the groins. Maps and profiles made in 1924, 1932, and 1936 gave an opportunity to study these changes in detail in a model.

To determine the reliability of relatively small-scale hydraulic models in reproducing changes to beaches by erosion, a movable-bed model [HALL, 1938] was built to reproduce the groins and a portion of the shore line in each direction (see area covered by model in Fig. 3). The model was 12 feet by 20 feet in plan with a horizontal scale of 1:150 and a vertical scale of 1:49, giving a distortion of 3.06. A wave machine was so oriented in the model to give a wave front alignment near the shore similar to that determined from the refraction diagram shown in Figure 3 for a wave period of nine seconds coming from the west. Tide was simulated by supplying and draining water to and from the model. Sand was supplied in varying quantities to simulate the littoral drift estimated in the prototype to vary from 700 to 1000 cu yd per day. With the bottom molded to the 1924 topography, runs to equilibrium were made, this equilibrium condition simulating approximately the 1932 condition in nature. Repeat runs showed the ability of the model to reproduce itself. By cutting off the supply of littoral drift and allowing the beach to erode, it approximated the 1936 condition in nature. This model produced good general results but did not reproduce the prototype too accurately. Some of the discrepancy can, of course, be attributed to the irregularity in nature of wave period, height, and direction, and the varying material comprising the beach, as previously mentioned.

Santa Monica breakwater--The problem in the vicinity of the Santa Monica breakwater is similar to that at Santa Barbara, namely, an estimated 800 to 1000 cu yd of sand daily, which moves southward along the shore, was intercepted by construction of the breakwater. The breakwater was constructed parallel to the shore (see Fig. 4) with the expectation that the sand transported by littoral currents would continue to move uninterrupted down the coast. Wave refraction around the breakwater, however, is such that the littoral current carrying the sand is greatly reduced in strength and shoaling results. The extent of shoaling to the north, the resulting scour to the south, and the refraction pattern behind the breakwater are seen clearly in the aerial photograph shown in Figure 5.

In order to determine how closely a hydraulic model could reproduce conditions observed in nature, a fixed-bed model [LAPSLEY, 1937] was constructed covering the area shown in Figure 4. The model scales were 1:700 horizontally, and 1:140 vertically. A wave machine was so located as to generate waves to approach the breakwater at an angle of 14 degrees (see Fig. 4), this being the prevaling wave direction observed in nature.

The fixed-bed of the model was molded with allowance for erosion over the areas where scour was expected. Before the first run was started, the bottom was molded to conform to nature

conditions by placing a layer of sand north and south of the breakwater where allowance had been made for erosion. Sand was fed into the model north of the breakwater at a rate which approximated a littoral drift of 1000 cy yd per day in nature.

In all runs, sand moved southward along the shore and formed a shoal behind the breakwater. The position of the shoal varied depending on the rate of sand feed and the height and period of the waves. In Figure 4 are shown the shorelines at mean lower low water for corresponding conditions in model and nature. In general the position of that part of the shoal above water conformed closely with the position in nature, whereas the profiles in model and nature are markedly different. As in the Santa Barbara study, such a relatively small-scale distorted model is of value in predicting major shoreline changes, but cannot be relied on for giving detailed changes.

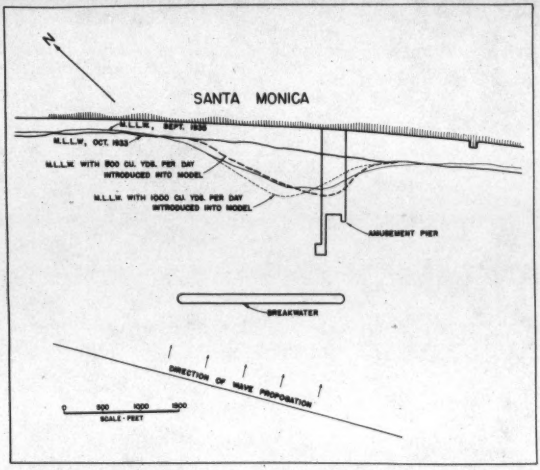

Fig. 4--Model study of beach erosion at Santa Monica breakwater

Cabrillo Beach--Outer Cabrillo Beach, located in the angle formed by the line of cliffs just east of Point Fermin and the north end of the San Pedro breakwater, is an artificial fill constructed in 1927 by pumping approximately 500,000 cu yd of sand from Inner Los Angeles Harbor (see Fig. 6). At the time of construction no effort was made to shape the beach so that its final configuration would approximate that of a beach formed by natural forces. The finished sand fill varied in height from 10 to 15 feet above mean lower low water, and the original bottom on which the sand was deposited varied from two feet at the west end of the beach to 16 feet or more at the east end near the breakwater.

After 1927 the beach eroded, and in 1938 a survey showed a gross loss of 154,000 cu yd of sand of which 44,000 cu yd had shifted into water deeper than ten feet. During the same period the beach inside the harbor, which was constructed simultaneously with the outer beach, showed a net gain of 53,000 cu yd of sand as a result of leakage through the breakwater.

As a result of the sand loss from the outer beach, the western end of this beach was completely denuded of sand, and the rocky bottom was exposed. The center and east end of the beach were eroded back from the original water line by as much as 200 feet.

In order to obtain information as to the most practical methods to be employed in stabilizing the beach and preventing further erosion, a model study of the area was made for Los Angeles County [GEE, 1938; and McAFFEE, 1939]. The model was undistorted and built to a scale of 1:50 with a movable bed. The area reproduced in the model is indicated in Figure 6. Waves were produced by a machine and tidal cycles were reproduced by manual control of the inflow and outflow

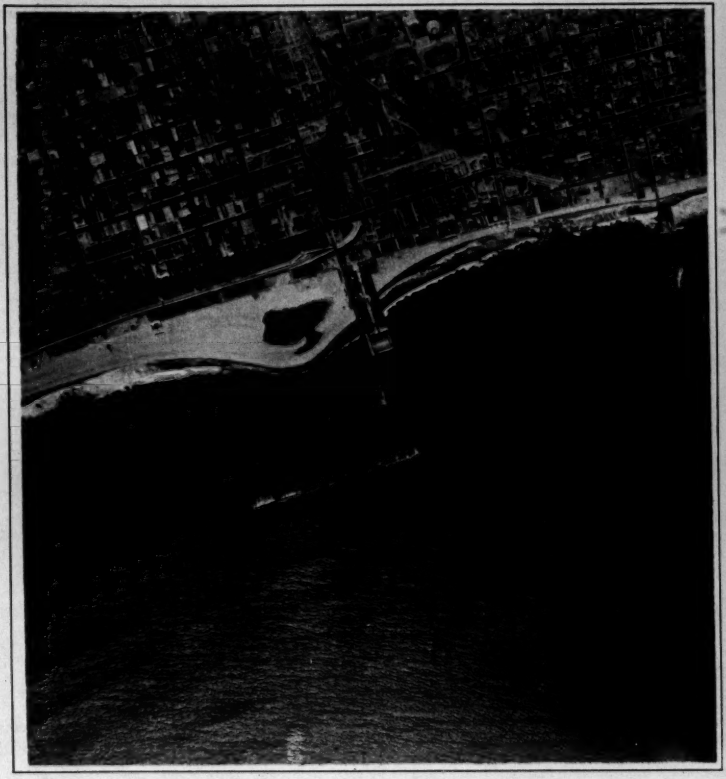

Fig. 5--Aerial photograph at Santa Monica breakwater, June 15, 1944; note (1) the wave refraction pattern in the lee of the breakwater, (2) the wide beach to the left and the eroded beach to the right of the main sand deposit, and (3) the large ground swell as well as small waves generated by local winds

valves. Because waves in nature approach the coast generally from the northwest but undergo refraction in the shallow water near shore, a refraction diagram was prepared (see Fig. 6) to aid in orienting the wave machine in order that the waves in the model would approach the shore line at the same angle as in nature.

The model was operated with various conditions of wave period, height, and direction, with the beach molded to various initial alignments. Experiments were made with and without a permeable breakwater and with groins installed to control the littoral drift of the bed material.

The model proved itself to be reliable by reproducing the changes occurring in nature between 1928 and 1936. The model clearly showed that erosion was caused primarily by the fact that the original shape of the beach departed radically from an equilibrium configuration; thus, waves broke at an angle with the beach, generating a strong littoral current which transported the sand eastward

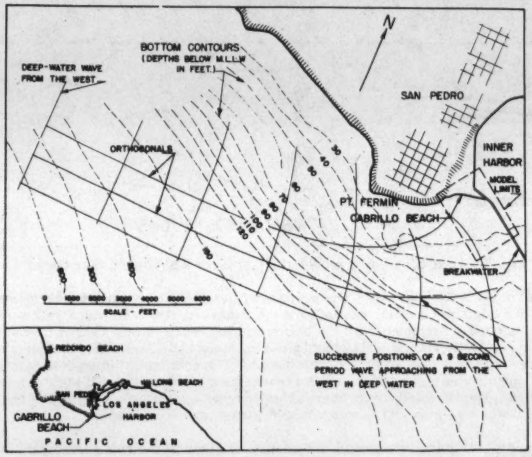

Fig. 6--Wave refraction diagram for Cabrillo Beach and vicinity

to be washed through the permeable breakwater or carried off-shore into deep water. In either case the sand was permanently lost to the beach and, hence, not available to build up the beach when the littoral current moved in the opposite direction.

The method recommended for stabilizing Cabrillo Beach, therefore, was to: (a) Replace the sand fill with a configuration parallel to the wave front at the breaking point. This alignment could be taken either from the model study or a refraction diagram (see Fig. 6). (b) Construct a groin at the east end of the beach, not less than 400 feet in length, and approximately perpendicular to the axis of the breakwater. The groin should have an impervious core and be sufficiently high to prevent sand passing over it. (c) Seal the San Pedro breakwater shoreward from its intersection with the groin, thus eliminating sand loss through the breakwater.

Lake Washington Ship Canal--The Lake Washington ship canal consists of a fresh-water channel connecting Lake Washington and Union and Salmon Bay with Puget Sound. The fresh-water lakes are regulated at an elevation of 25 feet above extreme low water in Puget Sound and connect with the Sound by means of the Ballard Locks. During the period from 1920 to 1922, a series of tests [BARDEN and SARGENT, 1928] on the Lake Washington ship canal showed that salt water passed through the Ballard Locks and penetrated to a distance of about five miles from the locks during periods of low flow. Even during periods of large runoff, the salinity below depths of 30 feet in Lake Union remained high.

In order to determine a more satisfactory means of preventing the contamination of the fresh-water basin at Seattle, a hydraulic model was built of Ballard Locks and the adjacent channel [FRIES and VINEY, 1933]. The effects of variation of the density of the salt solution on the velocities and distances of travel upstream of the salt-water wave also were observed, and thus served as a check on the theory for the velocity of a salt solution leaving a lock chamber [O'BRIEN and CHERNO, 1934]. The model (see Fig. 7) was of the fixed-bed type with scales of 1:480 horizontally and 1 to 108 vertically, and was provided with a siphon constructed to the proper size and operating head. Salt water was introduced to the locks by gravity from an auxiliary elevated tank.

The experimental work consisted of an investigation to determine the effectiveness of various combinations of sump, sills, baffles, and siphons in reducing the upstream flow of salt water.

The best means of controlling the upstream migration of salt water consisted of deepening and enlarging the upstream sump and installing a sill and a baffle, as shown in Figure 7, with their

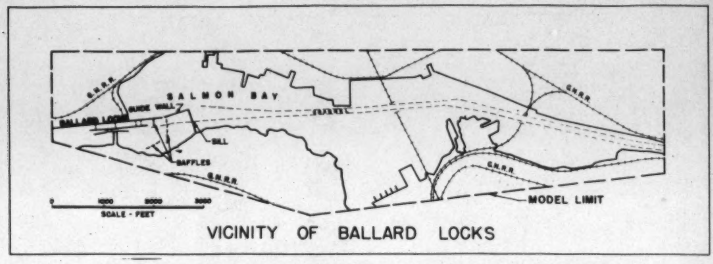

Fig. 7--Area covered by model study of Lake Washington Ship Canal

tops 32 feet below the water surface. The purpose of the sill, which extended completely across the channel at the depth mentioned, was to limit the sump and retain as much salt water as possible in the sump area. The purpose of the baffle was to reduce the current of salt water and interfere with surges in the sump. This combination of sump, sill, and baffle completely restrained the flow from two full lockages without necessitating the operation of the siphon, thus conserving a considerable quantity of fresh water. This arrangement of sump and sill also required less water than other systems tested, even when the siphon was operating, owing to the fact that dilution of the salt water was less and therefore the drainage was more rapid.

Summary--As previously mentioned, the results of some of the more important investigations made in the University of California model basin have been discussed. Other studies on specific problems included (a) an investigation of proposed plans for the prevention of silting in a log pond at Longview, Washington for which results are given in three reports [ANONYMOUS, 1935], (b) an investigation of the hydraulic forces on a caisson at Pier 5 of the Tacoma Narrows Bridge [O'BRIEN, 1939], and (c) an investigation of debris barriers for the United States Forest Service [BERMEL and SANKS, 1946; and JOHNSON and MINAKER, 1944]. Investigations of fundamental application in studying surface waves and related phenomena include, surging in harbors [BROSHOUS, 1938]; the effect of wall friction on waves in a channel [O'BRIEN and CHAFFIN, 1942]; the measurement of the orbital velocity of particles accompanying oscillatory wave motion [MITCHIM, 1940]; the transformation of waves in shallow water [STELZENMULLER, 1941]; the equilibrium slopes of sea beaches [MEYER, 1936; and WATERS, 1939]; equilibrium sand slopes in front of sea walls [DORLAND, 1940]; and the transportation of sand by littoral currents [KRUMBEIN, 1944]. Studies also were made of wave refraction about a breakwater [McCRONE, 1940]; around an island [WILHOYT, 1940], and in a submarine valley [MILNER, 1941].

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REPORT OF COMMITTEE ON GROUND WATER, 1945-1946

S. W. Lohman, Chairman

H. F. Blaney
E. B. Burwell, Jr.
Willard Gardner
C. S. Howard
C. E. Jacob
G. W. Musgrave
A. M. Piper
Roger Rhoades
N. A. Rose
Max Suter
A. C. Swinnerton
C. V. Theis
C. K. Wentworth
L. K. Wenzel

The principal activity of the Committee during the year was the arranging and presentation of a symposium on methods of estimating ground-water supplies. The response was gratifying and resulted in the presentation of 11 interesting papers at the 1946 meeting. The report of the Subcommittee on Permeability by C. E. Jacob, Chairman, is given as Appendix A. At a meeting of the Executive Committee of the Section of Hydrology in June 1946, this Subcommittee of the Committee on Ground Water was changed to the Committee on Permeability of the Section of Hydrology, with Jacob continuing as Chairman. This will give the new Committee much greater latitude in dealing with a subject which is of concern to several of the Research Committees.

A. C. Swinnerton returns as a member of the Committee after an extended absence on important war work. His first post-war paper on "The Hydrology and Physiography of Limestone Terranes," includes information on recent work in Okinawa, Puerto Rico, and several parts of the United States.

Paul D. Torrey has contributed a report on the "Significance of Water Injection in Oil Reservoirs," which is given as Appendix B.

Following the resignation of H. T. Stearns from the Committee, Chester K. Wentworth (Board of Water Supply, Honolulu, Hawaii) consented to serve on the Committee to report on Hawaii and other islands of the Pacific. His report on hydrology in Hawaii follows this report.

P. E. LaMoreaux (U. S. Geological Survey, Alabama)--The work in progress includes an investigation of the ground-water resources of the Tertiary area, comprising the southern one third of the State, involving a study of fluoride in ground waters used for public supplies; an investigation tion to determine the extent of sea-water encroachment in the vicinity of Mobile; and a study of the geology and ground-water resources of Mobile and Baldwin Counties.

S. F. Turner (U. S. Geological Survey, Arizona)--Under special authorization from the State Legislature, the geology and ground-water resources of each ground-water basin in the State will be studied and reported on to assist the Legislature in formulating a ground-water control law; a research study is in progress on the use of electrical resistivity methods as an aid to ground-water investigations; studies of the geology and ground-water resources are being made of the Globe area, the Prescott area, and the Verde River Valley; and the state-wide observation-well program and collection of pumpage records is being continued and expanded.

H. F. Blaney (U. S. Soil Conservation Service, California)--During the 1945-1946 season, the Division of Irrigation and Soil Conservation Service continued research drainage studies of irrigated lands in Imperial Valley, California in cooperation with the Imperial Irrigation District and other agencies. Laboratory and field measurements were made of the coefficient of permeability of aquifers at different depths in connection with the design of tile spacing for farms needing drainage.

Water-spreading studies were continued in the upper San Joaquin Valley during the year, in cooperation with the United States Bureau of Reclamation, the State Engineer of California, the United States Regional Salinity Laboratory, and local water storage districts. A progress report on this joint investigation prepared by Dean C. Muckel, summarizes percolation-rate data from test ponds located on different soil types and given different treatments along with results obtained on large spreading areas varying from one to 134 ac in wetted areas.

At the request of the San Fernando Valley Soil Conservation District, a provisional report was made by Harry F. Blaney and William W. Donnan on the ground-water situation in San Fernando Valley, California. Comparative data indicate the average annual rainfall for the period 1936-1943 to be 141 per cent of normal; the highest average for any previous seven-year record was 129 per cent. The contribution to the ground water from rainfall on the valley floor, return waters from irrigation, water spreading, and mountain runoff during the 1936-1943 period created a high water-table problem in local areas of the valley which may require a drainage system.

S. W. Lohman (U. S. Geological Survey, Colorado)--Field work has been completed on the sump-drain study in the San Luis Valley in cooperation with the Colorado Water Conservation Board and the United States Bureau of Reclamation; field studies are in progress on the Grand Junction and Denver artesian basins; the observation-well program has been considerably expanded through active participation by W. E. Code, Colorado State Experiment Station; and new ground-water investigations have been planned for Baca County, the San Luis Valley, and the South Platte River Valley below Kersey.

W. O. Smith (The Hydrologic Laboratory, U. S. Geological Survey, District of Columbia)--The study of some hydrologic problems is greatly simplified by the use of electrical conductivity measurements in scaled models. In the investigation of others, electrical analyzers are very helpful. The Survey is at present constructing low conductivity electrolytic models. An electrical analyzer of the resistance-capacity type will be constructed for use in the study of nonsteady flow in confined aquifers.

Two dimensional parallel plate models of the type devised by Hele-Shaw are being studied with a view to their use in ground-water problems involving either steady or unsteady flow.

C. E. Jacob (U. S. Geological Survey, District of Columbia)--A conference with W. F. J. M Krul, Director of the Government Institute of Water Supply of the Netherlands, and several of his colleagues, discussed a monograph entitled "Recent ground-water investigations in the Netherlands," of which Krul is co-author and which is one of a series of monographs on the program of war-time research in Holland. This describes investigations that were continued during the occupation, principally in connection with water supplies in the Netherlands. Studies have been made of the safe yield of ground water in the dune areas, in which a stable balance must be maintained between fresh and salt water. In some places the problem is complicated by the fact that there is an underflow of salt water landward from the sea beneath the dunes to the polders. A unique installation has been made at Castricum comprising four lysimeters, each 25 m square. It is hoped that by means of these lysimeters, data may be collected on the effective rainfall under different conditions. Natural conditions of vegetation and surface texture are capable of simulation in the large lysimeters.

Studies have been made of the mechanics of ground-water movement under the unusual conditions encountered in the polders of Holland. These low-lying areas that have been reclaimed are underlain by a semipermeable clay which, in turn, is underlain by a continuous and permeable sand. In order to determine the quantity of water that must be drained from the polders to maintain the water table at a given level, analyses must be made of the ground-water movement, giving consideration to the upward or downward leakage through the semipermeable layer. A report on this problem was contributed by Steggewentz and Van Nes at the International Meeting in Washington in 1939.

Ground-water model research has been under way in the Netherlands to study the nonsteady flow of water in unconfined ground-water bodies. Glass-plate models of the Hele-Shaw type are being used to study the influence of precipitation and irrigation on the water table in a typical dune area.

The recharging operations practiced on a large scale by means of a system of canals and wells at the water works of the City of Leyden have been described in some detail. The monograph on ground-water investigations includes a bibliography containing brief abstracts of literature published since 1939 and that published prior to 1939 on ground-water supplies in the Netherlands.

H. H. Cooper, Jr. (U. S. Geological Survey, northern Florida)--A deep-well current meter was used to explore a well 2130 feet deep at Fernandina, Florida. The exploration indicates that large quantities of fresh water may be obtained from formations that lie below the bottoms of other existing wells, which are generally less than 1200 feet deep. An extensive pumping test was made on the artesian limestone formations at Fernandina in 1943, which was not reported

previously. Seven wells that were supplying 28 million gallons of water a day to Rayonier, Inc., a large rayon mill at Fernandina, were shut down for a period of ten days. During the shut-down, and for about two weeks thereafter, water levels and artesian pressures in neighboring wells were measured periodically. As a result of the shut-down, the artesian pressure in a well eight miles from the pumped wells rose two feet. Probably the recovery would have been detectable at more than twice this distance if the shut-down had been of sufficient duration.

G. G. Parker (U. S. Geological Survey, southern Forida)--The most important problems are those in connection with salt-water encroachment in the coastal areas of much of peninsular Florida, particularly in Dade County, where a water-control program is now being effected. In Dade County chloride-control dams are being installed in all tidal canals with the two-fold objective of (1) excluding salt water from canals upstream from each dam; and (2) raising groundwater levels and thus increasing the weight of fresh water available to depress the salt-water wedge encroaching at depth in the aquifers.

The State Water Survey is doing work on electrolytic corrosion in wells and in cooperation with the State Geological Survey is directing the rehabilitation of wells by acidification, chlorination, treatment with CO_2 or other means.

F. H. Klaer, Jr. (U. S. Geological Survey, Indiana)--The main phases of the work include a state-wide program of observation wells, including about 150 wells measured weekly, 25 of which are equipped with water-stage recorders; a state-wide inventory of water wells; and detailed quantitative investigations of ground-water resources in the South Bend, Kendallville, Lebanon, and Decatur areas. A research project to study artificial recharge, quantitative methods for determining underground storage, and average annual recharge and general trends in water levels has recently been established in cooperation with Purdue University.

H. G. Hershey (Iowa Geological Survey)--Geologic and hydrologic data are being collected in Iowa on a state-wide basis through contacts with drillers. Samples of well cuttings are obtained together with data on the constructional features and production of wells. Pumping and production tests are made on some of the larger wells. Detailed sub-surface studies of the Mississippian and Ordovician systems of rocks are being made. Maps showing the piezometric surface for some of the more extensive aquifers in the State are being prepared. A network of observation wells has been established for periodic measurements.

M. I. Rorabaugh (U. S. Geological Survey, Kentucky)--An intensive investigation of an area of 30 sq mi in Jefferson County southwest of Louisville included the test-pumping of a well for 35 days and measurement of water levels in 17 observation wells, three of which were in the Ohio River, accompanied by collection of data on temperature of river and well water, river stage, and chemical and bacteriological analyses of well water. Preliminary computations indicate that infiltration of river water can be developed to the extent of about six gal/min/ft along the river. An area along the Ohio River northeast of Louisville also is being studied to determine available supplies from infiltration.

P. H. Jones (U. S. Geological Survey, Louisiana)--The cooperative ground-water investigations in Louisiana during the fiscal year 1946 have been concentrated in the rice-farming region of the southwestern part of the State, where a program of monthly water-level measurements in some 130 key wells in 12 parishes has been followed as a basis for making a series of piezometric maps. The geology is relatively simple and the problem is primarily of an engineering nature, as almost all wells tap a single continuous aquifer. Pumpage inventories using key wells will be made when irrigation is in progress. Discharges of wells will be measured using the trajectory method checked by use of Parshall flumes. An investigation of salt-water contamination in this same aquifer is planned through the use of a deep test hole near Jennings, and through a widespread water-sampling program.

R. R. Bennett (U. S. Geological Survey, Maryland)--The cooperative ground-water investigations in Maryland were enlarged considerably during the fiscal year. A study was started of the correlation of the water-bearing formations in the entire Coastal Plain of Maryland involving the detailed microscopic examination of drill cuttings, identification of microfossils, and recording of other characteristics of the strata penetrated in a well.

Electrical logging, determination of hole diameter, mud-salinity logs, and other tests in connection with exploratory test drilling have proved to be of considerable value in determining the extent of salt-water contamination and the detailed character of the goelogic formations.

W. T. Stuart (U. S. Geological Survey, Michigan)--On studies in the northern peninsula of Michigan the problem is to determine, if possible, the means of reducing the costs of handling mine waters in the iron-ore producing areas. Although the problem is mainly economic, many new theoretical ideas are being tested and much experimental work is being done. A map outlining the glacial-drift basins and a water-table map showing the ground-water reservoirs and their contributing sources of recharge are being prepared. Recharge is being studied by observation wells and by seepage runs on the river, creeks, and mine-waste ditches. Discharge is studied by making pumpage inventories and seepage runs in the discharge area of the ground-water reservoirs. The physical characteristics of the reservoirs are studied by means of controlled pumping tests. Beyond this point the investigation departs somewhat from the usual lines. Studies are being made of the ability of both the ore and the non-ore formations to transmit and store water, and of the relationship of head in the glacial drift to the volume of water transmitted by the rock formations. By means of an extensive chemical study, it is hoped that information may be gained on the changes in quality as the waters percolate downward from level to level in the mines. As a by-product of these studies, it is hoped that clues may be found as to the role played by ground water in the concentration and enrichment of the ores. Information as to the surface-sealing properties of the iron sludge from the mine waters in the reduction of percolation in the waste ditches also is being studied.

I. C. Kammerer (U. S. Geological Survey, Mississippi)--The cooperative ground-water program has centered upon a study of the ground-water resources of Jackson. In addition to the well and pumpage inventories, seven pumping tests were conducted. The average daily pumpage was about 3 1/2 million gallons from wells and seven million gallons from Pearl River.

H. A. Waite (U. S. Geological Survey, Nebraska)--Except for test-drilling operations carried on in the southeastern quarter of the State, most of the cooperative ground-water work in Nebraska beginning in the fall of 1945 was devoted to investigations forming a part of the Missouri River Basin program participated in by the Bureau of Reclamation. These investigations included a detailed study of the lower Platte Valley between North Platte and Fremont, and less detailed studies in the Cambridge-Frenchman, Bostwick, and North Republican areas in the Republican Valley; the Boelus area in the Middle Loup Valley; and the Box Butte area embracing a large area of sand hills east of Alliance.

The studies in the lower South Platte Valley involved quantitative estimates of the capacity of the ground-water reservoir requiring determination of the specific yield and transmissibility of the water-bearing materials by field pumping tests and laboratory methods.

T. W. Robinson (U. S. Geological Survey, Nevada)--The current program of cooperative ground-water investigations in Nevada which began with the investigation of the Las Vegas artesian basin in July 1944 was expanded on July 1, 1945 to a state-wide program to include the systematic investigation of all the valleys in the State with emphasis on the development of ground water for irrigation.

H. C. Barksdale (U. S. Geological Survey, New Jersey)--The state-wide ground-water program will include the preparation of a report on each county and the evaluation of each of the major aquifers, some of which extend over large parts of the State. The safe yield from some of the major aquifers as a whole may become a matter of concern in the not too distant future, as it has already in local areas. Local intensive pumping of ground water has developed a need for artificial recharge and works for this purpose, generally involving water-spreading, have been constructed at several places. As opportunity permits studies are being made to evaluate the effectiveness of such methods and the diminution of intake rates caused by silting.

M. L. Brashears, Jr. (U. S. Geological Survey, New York)--In the past the shallow-lying glacial sands have constituted the chief source of ground water on Long Island. Lately, however, withdrawals from the deeper-lying Cretaceous beds have increased steadily and encroachment of sea water has occurred, requiring additional studies of these artesian aquifers. In 1946 an extensive study of the Lloyd Sand, the most deep Cretaceous aquifer, was begun. In April 1945 the Survey in cooperation with the New York Water Power and Control Commission began a comprehensive investigation of the ground-water resources of the entire State.

M. J. Mundorff (U. S. Geological Survey, North Carolina)--Investigations have been completed on the geology and ground-water resources of the Greensboro and Charlotte areas, both of which are in the Piedmont section, and reports on these areas are now in preparation. In December 1945 a research project was begun on the usefulness of the electrical resistivity method for selecting well sites in the granites, gneisses, slates, and schists of the Piedmont section. The idea is based on the known fact that the instrument will indicate the presence of water-soaked fracture zones,

quartz veins, or other structures that generally yield more water than the surrounding rock. Studies of the geology and topography are employed to select suitable areas of a few acres, and then the geophysical apparatus is used to select the specific sites. Drilling the selected sites should give information aiding in the interpretation of the results and also will indicate whether the method gives any better results than basing the selection of well sites on geologic and topographic evidence alone.

E. I. Schaefer (U. S. Geological Survey, Ohio)--The cooperative ground-water program in Ohio has been expanded into a comprehensive program covering the entire State. Water-stage recorders are being installed on selected wells tapping all of the important aquifers both in urben and in rural areas. An investigation is being planned of the Toledo area in Lucas County, where all ground-water supplies are obtained from the consolidated rock formations.

N. A. Rose (Lockwood and Andrews, Engineers, Houston, Texas)--A study of the subsidence of the land surface in the industrial area of Texas City resulting from heavy withdrawals of ground water shows that since 1942 there has been a very gradual subsidence of the land surface in the area occupied by two of the large industrial plants in Texas City. The subsidence was brought to light when routine leveling traverses at the plants would not check out, and when breaks occurred in the pipe of the distribution system and clogging was noted in the sewage lines. According to leveling surveys, the maximum amount of the subsidence in the area is slightly more than two feet. The extent of the area in which the subsidence has occurred cannot be accurately determined because of the absence of benchmarks and reference points outside of the properties of the two plants; however, a rough estimate of the affected area is about six sq mi. Recent data shows that the subsidence is still in progress but at a greatly reduced rate. Approximately 25 million gallons of ground water is withdrawn daily in the Texas City area, 60 per cent of which is pumped from the wells of two plants affected by the subsidence. The water is derived from two aquifers; the upper sand averages about 300 feet in thickness and the lower sand about 250 feet. Both sands contain numerous layers and lenses of clay. The two aquifers are separated by a bed of clay that averages about 75 feet in thickness. Since 1936 the artesian pressure in the upper sand has declined about 160 feet and in the lower sand about 120 feet.

It has been tentatively concluded that the subsidence is caused by the compression of the clay bed between the aquifers and of the clay laters and lenses within the aquifers. The decline in artesian pressure in the two aquifers caused by the large withdrawals of ground water caused the clays to compress, thus releasing water from storage.

H. E. Thomas (U. S. Geological Survey, Utah)--A study of the geology and water resources in Tooele Valley is approaching completion. This valley is different from most of the closed basins of the Basin and Range province in that it is open toward Great Salt Lake. Because of the low permeability of sediments under the lake, however, subsurface movement of ground water northward appears to be small, and the principal discharge from the valley aquifers appears to be by springs bordering the northern part of the valley, where the adjacent mountains have provided coarser material than that in the central and northern parts of the valley.

A report is being completed on the ground water in Pavant Valley which, with previously published reports on the leakage of flowing wells and on the geology, will give a comprehensive view of the ground-water hydrology in that area. Pavant Valley is bordered on the west by basalt flows of Pleistocene and in part post-Bonneville age. Some ground water is discharged from Pavant Valley through these lavas, and gives rise to springs farther west. Most of the aquifers in the valley, however, appear to be closed to the west and yield water under artesian pressure. Some of the largest flowing wells in Utah have been drilled in the vicinity of Flowell.

A detailed study has been started of the ground water in the Bountiful area, just north of Salt Lake City, which is a narrow plain bordered on the east by the Wasatch Range and on the west by Great Salt Lake. Experiments are being conducted involving the spreading of water over the shore terraces of Lake Bonneville along the Wasatch front, to ascertain whether the artesian aquifers or the overlying unconfined zone receives the bulk of this artificial recharge.

A large number of samples of well water for chemical analysis have been collected in the vicinity of Ogden as part of an intensive investigation of the East Shore area bordering Great Salt Lake. These analyses have served to outline an area in which water is excessively mineralized. The northern boundary of this area is a fairly straight line joining El Monto Hot Springs and Utah Hot Springs, and it is evident that the mineralized water rises along a fault. In a rudely triangular area south of this fault, mineralized water is encountered in most, but not all, aquifers.

D. J. Cederstrom (U. S. Geological Survey, Virginia)--A reconnaissance survey was begun of the ground-water supplies of the entire State. Reports are now nearing publication on the Roanoke area, the chemical character of ground water, foraminifera in Upper Eocene Coastal Plain sediments, and an inventory and discussion of the geology and hydrology of the Coastal Plain south of the James River.

Consideration is being given to the possibility of utilizing fresh ground water for recharging in areas where the ground water is brackish, such as the highly industrialized Hampton Roads area.

Roger Rhoades (U. S. Geological Survey, Washington)--In connection with ground-water studies being made at Coulee City by the United States Bureau of Reclamation, it was desireable to obtain water-level measurements from a number of aquifers without the necessity of drilling an observation hole to each. A multiple packer was devised and has been successfully installed in two Nx drill holes which will permit readings of water level in as many as five different water-bearing horizons in each hole.

Howard F. Johnston (U. S. Geological Survey, West Virginia)--Studies are being continued of the recharge of the Ohio River alluvium, aided by two pumping tests conducted by a large industry.

Coal-mine drainage, which constitutes the greatest discharge of ground water in the State, is being studied. Most of this water is wasted by disposal into surface streams. In many places the high acid content of the mine water causes serious contamination of some of the streams.

The contamination of fresh waters by oil-field brines is a serious problem in some parts of the oil and gas producing areas of the State. The use of well-exploration equipment is being considered in the solution of this problem.

U. S. Geological Survey,
Denver, Colorado

APPENDIX A--REPORT OF THE SUBCOMMITTEE ON PERMEABILITY, 1945-1946

C. E. Jacob, Chairman

During the year 1945-1946 steps were taken to enlarge the membership of the Subcommittee on Permeability of the Research Committee on Ground Water of the Section of Hydrology. This was done to insure reaching workers in all fields concerned with fluid permeation so that they might have a voice in the establishment of standardized nomenclature and notation. Contacts were made, or are being established, with the following technical societies asking them to designate one or more persons to represent their organization on the Subcommittee on Permeability:

American Association for the Advancement of Science
American Association of Petroleum Geologists
American Ceramic Society
American Institute of Mining and Metallurgical Engineers
American Petroleum Institute
American Society for Testing Materials
American Society of Agricultural Engineers
American Society of Civil Engineers
American Society of Mechanical Engineers
American Standards Association
American Water Works Association
Geological Society of American
Highway Research Board
Inter-society Council for Textile Research
New England Water Works Association
Society of Economic Geolgists
Society of Economic Paleontologists and Mineralogists
Soil Science Society of America

Also it is hoped that the other research committees of the Section of Hydrology will be adequately represented in this undertaking, particularly the Committees on Runoff, Infiltration, and Physics of Soil Moisture.

A thousand reprints of the report of this subcommittee for 1944-1945 [Trans., v. 27, no. 2, pp. 245-273, 1946] have been printed. It is planned to circulate these reprints widely both here and abroad to provide a basis for further discussion. The opinions of the new members of the

enlarged committee will be published in a later report and will also be reprinted for wide circulation.

If it should appear that it is possible to arrive at a widely acceptable system of nomeclature and notation for permeability in the English-speaking countries of the world, it will be suggested that this matter be made the subject of discussion also at the next meeting of the International Union of Geodesy and Geophysics in Norway in 1948.

U. S. Geological Survey,
Washington 25, D. C.

APPENDIX B--SIGNIFICANCE OF WATER INJECTION IN OIL RESERVOIRS

Paul D. Torrey

In many of the older oil fields of the United States, where production cannot be maintained at a profitable rate because of small yield brought about by the dissipation of natural reservoir energy, greatly increased recovery is being secured by the artificial injection of water into the oil-bearing rock. This interesting and unique technique has found its widest application in fields where the primary production of oil has been mediocre or inferior.

The discovery of the benefits which can result from water injection was made accidentally in Pennsylvania about 40 years ago when it was found that improperly abandoned wells were permitting surface water to enter the oil sand. Increased oil production in nearby active wells was noted in the course of time, and it soon became evident that the water was concentrating the residual oil content of the sand and pushing it forward toward producing wells. The importance of this notable discovery received little publicity for many years, for it was illegal in almost every oil-producing state to introduce water into any oil-bearing horizon purposely. Subsequently, when it became apparent that substantial increases in oil production and recovery could be secured by water injection, appropriate legislation, permitting the practice, was enacted in many states. At the present time, water-flooding of oil sands is responsible for the greater part of the crude produced in eastern states, and is becoming a more important source of oil supply in certain mid-continent fields.

The amount of water required for flooding purposes,is generally, quite considerable, and frequently exceeds the annual rainfall over a given productive area. Therefore, particularly in arid or semiarid regions, supplemental supplies of water must be developed either from streams or underground sources. Originally, it was believed that virtually chemically pure water was essential for successful water flooding, but in recent years satisfactory results have been obtained by the use of natural saline solutions.

Since the water used for flooding must be forced into what is usually very finely porous rock, it must be free from all sediment and any other material which might tend to plug the pore spaces and thereby impede the steady introduction of water into the reservoir. Elaborate plans for the purification and filtration of water are required frequently.

The early water-injection projects utilized existing wells principally. It was soon determined that better results could be secured by a more systematic arrangement. Therefore, it has become common practice to drill alternating rows of injection and producing wells in accordance with some fixed geometric pattern. By application of water pressures to the reservoir, sometimes double the normal hydrostatic head from the surface down to the top of the oil sand, it has proved to be possible, in certain operations, to cause the producing wells to flow, thereby reducing the cost of production materially.

Water-flooding is undoubtedly the greatest conservation measure that has been developed for application in older fields which were not exploited in accordance with the most efficient methods of reservoir control. It is estimated that almost four billion barrels of oil can be recovered in the United States by water flooding which otherwise could not be produced economically by any other known process.

Houston, Texas

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HYDROLOGY IN HAWAII, 1946

Chester K. Wentworth

Consideration of ground-water hydrology in Hawaii independently of meteorology and surface-water studies is scarcely practicable. The unit provinces, within which somewhat comparable ground-water conditions are found, are so small, and the contrasts in annual rainfall in very short distances so marked, that each local problem requires attention to the entire hydrologic cycle. For example, the District Engineer of the U. S. Geological Survey for surface water is also responsible for measurement and some control of artesian wells throughout most of the Territory and also maintains some rain gages. In turn, the Board of Water Supply in the Honolulu area carries on measurements of rainfall, stream flow, tunnel yields, static levels of wells, shafts, and the general water table. Varied patterns of measurement and study of rainfall, water levels, and discharge quantities are also carried on by numerous other public agencies, agricultural groups, and individual plantations.

A part of the hydrologic study in the Territory is purely scientific inquiry, but to a large extent the collection of data and much of the analysis is directly related to use of water. Apart from the soil, which must be used where it lies, water is the chief mineral resource of the Territory and the pattern of its occurrence and circulation is the deciding factor in practically all agriculture and much other industry. As elsewhere, the initial exploitation and areal commitment has usually preceded any systematic evaluation of water resources. Hydrologic studies are taken up after the appearance of operational problems; in some instances after substantial failure or disappointment has occurred.

Rainfall records were made at a few places by interested individuals during early days of missionary settlement and before annexation in 1898, but only a few presently operating stations have a record commencing before 1900. The U. S. Weather Bureau Office at Honolulu has operated since 1904. Using data from cooperating observers, by 1918 it had developed a general picture of the astonishing contrasts in rainfall due to elevation, direction of exposure and the surrounding topography. Owing to lack of settlement and relative inaccessibility, adequate daily records have at all stages been lacking from many inland and high-level stations, though special effort has been made by some plantations and other agencies to establish and maintain gages in such places. Without intending to criticise any individual, it is fair to state that the policy and practice of the United States Weather Bureau has been too limited and restricted by directives adapted to broad regional observation on the mainland of the United States to develop and support a local program or recording and analysis suited to the fine-meshed variations of rainfall in Hawaii. Neither the requirements of practical water-supply inventory nor of fundamental meteorology have been met by any agency dealing homogeneously with the entire Territory, though much has been learned through local coverage by the Board of Water Supply, and by certain plantations. It can hardly be doubted that the money and manpower devoted to rainfall measurements in the whole Territory, could under coordinated planning and with little addition, carry a general service of measurement and analysis that would be of equal value to the areas now specially covered and also of much systematic value. However no such general program has yet been established.

The most complete coverage of hydrologic recording is that of stream gaging by the U. S. Geological Survey with its related records of wells, shafts, and tunnels. This program was commenced in 1909 and with territorial cooperation has been carried on continuously since then. Records of stream flow for many principal streams give a valuable picture of total and mean discharge and of duration-discharge. Taken with areas of drainage basins some rough rates of mean discharge per square mile can be calculated but with rather large and not fully understood differences from basin to basin. Indicated quantities at the gage station form a valid base for practical application at that point. However, they do not permit confident calculation of total runoff from complete segments of islands which include areas of lower slopes and lesser rainfall lying between the chief streams and not tributary to the gage station. Knowledge of total runoff in relation to rainfall of various distribution in time and space is quite insufficient as yet to solve some of the more specific problems of given areas

On transpiration and evaporation, data are even less adequate than for runoff or rainfall. Hawaii has so varied atmospheric, soil, and plant conditions, hence so many small natural provinces, that nothing like general mapping of transpiration or evaporation rates has yet been accomplished.

While a large body of data has been collected for such crops as sugar cane and pineapples, nothing generally applicable to areas of forage plants or natural watershed vegetation has been done. Data for two stations have been published but these show such variation from year to year and from one to the other, that only extremely general conclusions can be reached and they are certainly not an adequate base for calculation of transpiration or evaporation in mountainous watershed areas of value in hydrologic inventories. The writer is very doubtful if any methods of measurement of these losses in various forested mountain areas will ever closely approximate the true losses, or can be developed before the vegetation conditions become materially changed.

For many years data have been collected on heads, discharges, and salinity of artesian wells in the Honolulu, Pearl Harbor, Waialua, and Kahuku areas of Oahu, and the few artesian areas of other islands. Except for records kept by the Board of Water Supply in the past 20 years in the Honolulu area, these have been collected by the U. S. Geological Survey. To specialize in this work an artesian well engineer has been attached to this office. During the past 15 years a survey of geology and ground-water resources under the Geological Survey has been in progress, with partial financial support from the Territory of Hawaii. Ground-water data have been collected by the U. S. Geological Survey in collaboration and mostly published by the latter in connection with the geologic reports. With the recent increase in basal tunnels and shafts for development of the same water as that earlier taken chiefly by artesian wells, recording has been expanded to include these installations. For the past ten years, certain representative wells and shafts have been used as index stations from which monthly head records have been reported in the annual tabulation of water levels in the United States, published by the U. S. Geological Survey. During the past two years, three 12-inch wells have been drilled inland of the caprock in the Pearl Harbor area by the Board of Water Supply for observation wells. Another such well is to be drilled shortly and these are being fitted with concrete shelters and continuous recorders. It is expected that they will furnish records of the regional head of the free water table with less variation and disturbance from nearby pump operations than the artesian wells reported to date by the U. S. Geological Survey for this region.

The most extensive and continuous program of salinity determinations is that carried on by the Board of Water Supply, in part based on wells within the city area, both public and private, and in part on wells and other sources in the Pearl Harbor area, as a part of general survey in the public interest. While it is open to little doubt that increase in salinity is in progress in various areas under certain conditions, the discrimination between permanent changes and those due to extreme operating trends that cannot immediately be reversed is difficult and hinges in part on doctrines that are not established in detail. Unfortunately most salinity determinations in the past and the majority today are tied to operating discharges and therefore are more difficult to duplicate exactly in recurring measurements. Emphasis is now being given by the Board of Water Supply to making salinity measurements on wells at very small, but steady discharges, with the hope that it will be possible to very nearly repeat these conditions over a period of years and secure more valid data on what might be called real undisturbed salinity of the ground water adjacent to a given well.

For a period of about ten years after the establishment of the Board of Water Supply, and the adoption of an active program of conservation, the lowering of head in the Honolulu artesian area which had been in progress since the drilling of the first artesian wells in 1880, was somewhat arrested. By 1936 the gains caused by conservation had again been overtaken and under rapidly increasing draft, heads have been reduced so that both in 1944 and 1945 the summer heads were equal to the lowest position of record, with little improvement during subsequent winter periods. These conditions are mentioned as elements of the problem which can now be set forth in question form: (1) To what extent will lowered head result in increased permanent capacity caused by reduced natural leakage? (2) To what extent is the low rainfall of the period 1940-1945 really below normal and likely to be exceeded in subsequent years? (3) What are the relative effects of high draft and low rainfall in producing lowered heads at present? (4) To what degreee have recent high drafts been met by yield caused by lagging adjustment of the Ghyben-Herzberg lens to the established low head condition? (5) What relative balance between higher yield and lesser storage attending low heads and the reverse conditions with higher heads will constitute a suitable community policy?

These queries are not new to students of ground water; however they are peculiarly insistent in Hawaii where much is already known about hydrologic conditions, but where the problem must eventually be solved with a great deal of local precision to be of practical worth. These queries apply particularly to the Honolulu and Pearl Harbor areas and only slightly less emphatically to several other artesian areas on Oahu.

In several other areas where ground water has not been exploited overall problems of hydrology have been less fully explored and the need is still primarily for rainfall and runoff data. The hydrologic problem in Hawaii is peculiar in that in most sectors there is very little prospect that surface storage can be developed. Ground-water storage is of two sorts, that of confinement behind dikes where pressure heads of one hundred feet or more are found in some places, and that in the Ghyben-Herzberg lens. Because of the lack of surface storage, natural or artificial, and the lack of large streams of length greater than 10 or 20 miles, peculiar interest attaches to ground storage. The areas in which water is confined behind dikes are in general rather small and receive the rainfall of small areas. They are subject to progressive depletion and a part of the accumulated natural storage is necessarily lost as a result of development. In the past, tunnels have been driven and water allowed to discharge freely without provisions for control. Within the past few years it has become fairly general practice to install bulkheads and limit discharge to some extent. This represents a distinct advance in hydrologic understanding; some projects have accumulated several years of data toward a solution of the duration-discharge-storage rate problem. These projects have a great advantage over the Ghyben-Herzberg systems in that stored quantities are fairly closely indicated by recorded pressure heads and also that the problem of lag is more readily solved.

Enough has been said in preceding paragraphs to indicate the three outstanding problems in Hawaiian hydrology today. These are: (1) The amount and variations in amount of water annually available, (2) the relation between natural storage and the annual amount, considering both quantities stored and the rate and conditions of availability, and (3) the optimum conditions of utilization expressed in terms of amounts annually used and those held in storage and the program of achieving such conditions. The outstanding hydrologic problems in Hawaii are those of scientific control and management rather than of initial exploitation or development.

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Honolulu, Hawaii

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THE HYDROLOGY AND PHYSIOGRAPHY OF LIMESTONE TERRANES

A. C. Swinnerton

The United States Geological Survey and other government departments and state surveys were responsible for the greater part of the investigations carried on in the field of limestone hydrology in 1945. Very few reports of individual researches have been received. Many of the data reported bear the indications of direct war activities; most of the information was war-connected in its origin. It is to be anticipated that in another year or two individual investigations will again become significant and that some of the data from organizational research will begin to become coordinated.

Abstracts of work by Frank A. Swenson and D. J. Cederstrom, transmitted through the Geological Survey, were directly related to military operations in the Pacific.

On Okinawa the coralline limestone (Ryukyu) has a maximum thickness of about 200 feet. It rests unconformably on a basement complex of impermeable rocks; in places gravel deposits occur on the unconformity. The limestone is extensively exposed at the surface, but there is virtually no runoff from the limestone areas. Streams crossing from the basement complex areas to limestone regions either cut their valley-bottoms to the underlying rocks or pass underground into the permeable limestone, issuing as springs in the tidal zone. At least five springs with discharges of more than 1,000,000 gallons per day during the dry season were located. Yields from wells varied from place to place depending on the consolidation of the limestone, whether the aquifer was soft, porous rock, yielding small flow or hard coral which would support open caverns and give high yields when encountered. Structures, notably major faults and minor folds, exerted a great influence in controlling the location of underground streams and springs. In addition to water supply, problems included locating materials for structures, airstrips, roads, and surfacing mixes.

The Geological Survey's ground-water reconnaissance in Puerto Rico resulted in the following comments by C. L. McGuinness on the hydrologic and physiographic contrasts observed in that island: Limestone terranes with typical karst topography and underground drainage are well developed in Puerto Rico, as in the other major Antillean Islands. The principal limestone terranes are developed in the areas of Tertiary rocks that flank the island on the north and south. The Cretaceous metamorphic rocks, largely of volcanic origin, that form the core of the island include some limestones with karst topography and underground drainage developed only locally.

Hydrologic features typical of limestone terranes are well developed in the limestone belt along the north coast, particularly in the western part of the belt, where the limestones are thickest and have been uplifted highest above sea level. Chains of karst hills, known as mogotes or haystack hills, are abundant, and large areas are characterized by underground drainage. The limestones form productive aquifers in the major valleys that cross the limestone belt, where the water table is near the surface and the solution channels in the limestone are well developed. In the interstream areas the crevices appear to be fewer and smaller, though apparently developed to considerable depth, adequate to dispose of the rainfall, with a deep water table and with wells that do not yield as much water as in the lowland areas. The northwestern corner of Puerto Rico comprises an elevated limestone platform with underground drainage, in which the water table is far below the surface and few wells have been drilled.

The Tertiary limestones of the south coast appear to be somewhat less soluble than those in the north and features typical of limestone terranes are not well developed. Nevertheless the limestones of the south coast form valuable aquifers in certain areas where the alluvium is thin or absent.

Studies of the occurrence of ground water in the Lexington area of Kentucky are being made by the U. S. Geological Survey in cooperation with the Geological Division of the Kentucky Department of Mines and Minerals and several counties in the Blue Grass region. The studies thus far made by Dan K. Hamilton and reported through the Geological Survey indicate that the occurrence of the ground water is controlled almost entirely by solution cavities confined largely to joint planes and to a smaller extent to bedding planes. A large part of the solution takes place in the enlargement of vertical joint planes. The water is therefore restricted to a grid of vertical planes.

The tendency of water below, as well as at, the surface, to move toward topographic lows, has augmented the amount of water and the solutional development of the joint system below the surface valleys. The result, all other factors being equal, is a base level for this solutional process, which exists as a plane undulating 60 to 80 feet below the land surface with slightly overdeepened valleys.

F. Stearns MacNeil of the U. S. Geological Survey, presented a paper in abstract at the 1945 meeting of the Geological Society of America, calling attention to a large area of complete solution in eastern Alabama and western Georgia. It is now apparent that in Georgia, more so than in Alabama, this is a conspicuous feature. The Jackson and Oligocene limestones are completely dissolved back from their normal outcrop for over 50 miles, where they rise to form a solution scarp nearly 200 feet high. The area of solution in Georgia, known physiographically as the Dougherty plain, is a low, broad anticline. Over it once lay the very pure Jackson and Oligocene limestones. Their residues consisting of ferruginous sand and clay, and blocks of fossiliferous chert are extremely heterogeneous. They rest on the insoluble sand that originally underlay the limestone. The side of the (limestone) scarp and a strip back from it for a few miles are dotted with sink holes, and quite a few good sized streams disappear into the sinks, showing that the process is still continuing and working back.

Several of the state surveys have reported investigations relating to limestone hydrology, undertaken by themselves or cooperatively with the U. S. Geological Survey.

Robert R. Storm, reporting for the Illinois Geological Survey, writes: As part of the Survey's continuing investigations, data on limestone and dolomite aquifers are being collected and filed with other well records. Some of the available data on limestone aquifers will soon be published in a report on the ground-water geology of northeastern Illinois.

This Survey, in cooperation with the Illinois State Water Survey, has been systematically collecting data on the chemical treatment of limestone and dolomite wells, principally acid treatments. These data will eventually be analyzed and correlated and a report on acid treatment will be published.

As a result of the Survey's work on geophysical logging of water wells, many data have been collected on the electrical behavior of limestones and dolomites. Some of these data have been published in general papers on the logging work undertaken in Illinois.

In connection with the Survey's continuing investigations of the lead and zinc deposits of northwestern Illinois, data have been collected on the solution of limestone and dolomite and its relation to the position and structural relations of the ores. This work will soon be published in a paper on the origin of the ore deposits in northwestern Illinois.

Electrical logging and acid treatment of limestone aquifers is receiving attention in Missouri. John Grohskopf reports: Over much of the Ozark region the aquifers are siliceous dolomites. Lately acidizing of these dolomites has shown promise of markedly increasing the yield. While the technique is not thoroughly understood and many problems arise, it is believed that acidizing will become increasingly popular. It is planned to use certain wells for observation and others for drawdown and pumping tests. It is the intent to enter the field of electrical well logging along the lines now pursued by the Illinois Geological Survey. Information thus obtained will give us a better understanding of the porosity and permeability of the various aquifers, which in turn will be extremely helpful in choosing the depths at which a well should be acidized or shot.

Commenting on the relation of geology to water wells, Meredith E. Johnson, State Geologist of New Jersey, contributes the following information regarding the Kittatinny limestone aquifer in New Jersey: Overlying the Hardyston (formation), and very much overshadowing it as an aquifer, is the Kittatinny limestone. This is a series of blue and gray limestone beds having an aggregate thickness of 2500 to 3000 feet. They occur in several northeastward-trending belts in the northwestern part of the State and in many of the valleys in the Highlands. Like the Franklin limestone, the rock itself is dense and relatively impermeable; but it is traversed by many fractures and some of these have been enlarged by solution to such a degree that they carry a great deal of water. It is for this reason that although some wells drilled in the Kittatinny formation might well be called "dusters," the average yield of 56 wells having an average depth of 212 feet and drawing from the Kittatinny has been, according to our records, a little better than 90 gpm. Supplementing those data is a long-continued series of observations on the elevation of the ground-water table in a large area surrounding Phillipsburg which is underlain by the Kittatinny limestone. These show that the ground-water table in that area is relatively flat, and hence demonstrate that the ground water moves through the fractures in the limestone with relative ease and little loss of head.

Bulletin No. 49 of the Georgia Survey, published in 1944, deals with artesian water in southeastern Georgia. A. S. Furcron reports that it bears directly upon the hydrology of the Ocala limestone. The importance of this limestone as an aquifer from which such cities as Savannah and Brunswick, Georgia, obtain their water supply has been expressed. The dangers of salt water infiltration have been discussed.

Since that time there has been considerable work on the general geology of the Georgia Coastal Plain as part of a cooperative project involving the study of ground waters over the State.

John T. Lonsdale, Director of the Texas Bureau of Economic Geology, reports: About the only work which we have done on the hydrology of limestone terranes has been in central Texas, where F. B. Plummer has studied the underground water in some of the limestone areas, especially in the areas where springs are abundant. This work has not yet been published, but in general way it can be said that it consists in the study of the origin of the springs, the quality of the water, and the origin and character of travertine deposited near many of the springs.

Through E. B. Burwell, Jr., Principal Geologist in the Office of the Chief of Engineers, reports have been received from several of the Division and District Engineer offices. In the foundation engineering work of the War Department the problem of localized solution channels assumes great significance. Comments by Robert H. Nesbitt, Ohio River Division Laboratories, illustrate the dilemma: While investigating dam foundations in the pre-Cambrian limestones and dolomites of northwest Georgia and the Tertiary of the pan-handle section of Florida, we encountered weathering and solutional phenomena which in one case would indicate lithology as controlling, in another structure.

The local effects of structural control are amplified by excerpts from a letter by Alfred J. Holmberg, District Engineer Office, Nashville, Tennessee: Solution work extending well below ground-water table and controlled by jointing and bedding was conspicuous at the Douglas, Hales' Bar, and Kentucky Dams on the Tennessee River. Detailed descriptions with photos and drawings are available in articles in the Proceedings and Transactions of the American Society of Civil Engineers. Corresponding conditions occur at the Wolf Creek and Dale Hollow Dams on the Cumberland River system. The formations involved at both sites are the Leipers and Catheys limestones, immediately underlying the Chattanooga shale. Megascopically similar at both sites, these formations are crystalline but "impure," variably fossiliferous, thin-bedded with thicknesses from five inches to twelve inches predominating. The bedding planes are characteristically wavy and marked by shale laminae, and the Catheys has numerous thin hard black shale bands. The structure at both sites is gentle, the average dips being about three degrees, with local flexures reaching dips of eight to ten degrees. No fault displacements have yet been encountered, but jointing is conspicuously present. At both sites there is a marked increase in the number and individual extent of joints in these flexure areas. At Dale Hollow, there is very little solution widening of the joints but a really extensive solution widening of the bedding planes. At Wolf Creek, the reverse is true.

Work done in 1938-1942 in the Little Rock Engineer District, and reported by letter by George D. Roberts, indicates that regional physiographic processes and relationships play a role. He writes, in part: The presence of the old peneplain surfaces, such as the Salem and Springfield plateaus, into which the streams have entrenched themselves, coupled with the borings at many dam sites, gave an unusual opportunity to develop a theory of the typical weathering and ground-water profile of entrenched streams in limestone terranes. This typical weathering profile usually formed the basis for the (preliminary) selection of dam sites and its accuracy was confirmed so often by subsequent core borings that we came to rely on it.

Scientific cavern investigations, as such, have not been active so far as indicated by reports received by the writer. An interesting method of demonstrating the formation of caverns and sinks in miniature was published by Victor E. Schmidt, New York State Teachers College, Cortland, New York: Earth Science Demonstations in a Glass-Sided Trough, School Sci. and Math., pp. 6-11, January 1944.

The National Speleological Society has expanded its membership and its publications. Although the Society's interests are not primarily scientific, research investigators cannot afford to ignore the data which are to be gleaned from the activities of energetic "spelunkers." William J. Stephenson, 4825 North Lane, Bethesda, Maryland, is President; Charles E. Mohr, Philadelphia Academy of Natural Sciences, is Vice-President and has been assigned the task of developing the work of the Society's scientific committees.

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DISCUSSION OF

"MILITARY OCEANOGRAPHY IN TACTICAL OPERATIONS OF WORLD WAR II" by H. R. SEIWELL

[Trans., v. 27, pp. 677-681, 1947]

Charles C. Bates (Hydrographic Office, Washington, D. C., February 27, 1947)--If one construes the term military oceanography in the broad sense, namely, as the application of oceanography to warfare, Seiwell's paper presents an extremely limited picture of this field. For example, there is no mention of the extensive research and development carried out in subsurface warfare by the National Defense Research Committee and the Navy; of the studies in corrosion, currents, wave action, and transparency which were necessary for efficient mine warfare; or of the continued investigation of the drift of pack ice and icebergs across North Atlantic convoy routes and approaches to the Arctic bases directly affecting a large percentage of all trans-Atlantic ship movements above latitude 40° N. Likewise, reference is omitted to studies of the drift of life-rafts which made for more efficient search operations, to studies required to develop suitable anti-fouling paints, and to studies concerning the interaction of the sea and atmosphere which made for better smoke-laying and improved weather forecasting.

Should the discussion be restricted, as Seiwell has done, solely to oceanographic applications for the amphibious forces, it is fitting, for the sake of the record, to list the domestic groups which carried out important research, compilation, or publication in this field. These activities are the Beach Erosion Board and the Air Weather Service in the Army; Section 940 of the Bureau of Ships, the Aerology Section of the Office of the Chief of Naval Operations, the Hydrographic Office, and the Photo-Interpretation Center in the Navy; the Division of Tides and Currents in the Coast and Geodetic Survey; and, under special contracts, the Scripps Institution of Oceanography and the College of Engineering of the University of California; and the Woods Hole Oceanographic Institution.

In the field, the activities concerned with beachhead intelligence were fully as numerous as those located domestically. Thus members of underwater demolition teams, Marine reconnaissance companies, hydrographic surveying ships, harbor companies, and terrain intelligence teams supplied valuable information as did oceanographers, photo-interpreters, engineering officers, geologists, and oceanographic meteorologists.

The rest of this discussion is limited to a description of the work of the oceanographic meteorologists because the writer is fully acquainted with the development of that field. During the War, practically all the forecasting of sea, swell, and surf conditions was accomplished by meteorologists serving either in a staff capacity or as members of a weather station or central. Many of these officers had attended a special course given at the Scripps Institution of Oceanography. Special forecasts of sea, swell, and surf conditions were supplied during the invasions of Africa, Sicily, Normandy, Leyte, Luzon, Iwo jima, and Okinawa, and for the supply operations along the Aleutian chain. Probably the earlies quantitative forecasting of surf conditions in the field was accomplished by R. C. Steere, Comdr. USN, for the landings at Casablanca, Morocco, in 1942. Steere also devised the surf code which bore his name and which served as the basis for the Combined Surf Code accepted by both British and American meteorological services in 1944 for reporting and forecasting surf conditions. As the war progressed, mobile weather stations staffed by oceanographic meteorologists were assigned to beachhead commands in Normandy by the weather services of the Royal Navy and the U. S. Army. The on-the-spot forecasts on Omaha Beach, attributed by Seiwell to the "Military Oceanographic Unit," were actually prepared by Detachment YK of the 21st Weather Squadron, 9th Air Force, under D. W. Pritchard, First Lieut. AUS. The work of this outfit set the pattern for the beach-head weather stations planned for the invasion of Japan by the Army Air Force Weather Group in the Pacific.

The studies of wave heights in cargo operations, also attributed to the "Military Oceanographic Unit," were first made in the Swell Forecast Section, British Admiralty, by the writer, and subsequent studies of this nature were carried out at the beachhead by Detachment YK.

In the writer's opinion, the experience of the War demonstrated that, at least as far as forecasting of sea, swell, and surf is concerned, separate Army and Navy oceanographic services are not advantageous. Although the Navy and the Army may possess command of the same beachhead at different stages of an invasion, there is no driving need for a divorcement between the two in the preparation and presentation of the information, but rather a necessity for a joint effort in order to avoid duplication of work and to provide more personnel and facilities than either arm could provide by itself. An excellent example of such teamwork between the Army and the Navy and even between countries was the Swell Forecast Section, British Admiralty, formed by the Royal Naval Meteorological Service, the 21st Weather Squadron of the U. S. Army Air Forces, and Task Force 122 of the U. S. Navy. This forecasting unit, manned by Army and Navy meteorologists of both nations, furnished the basic sea, swell, and surf forecasts for the Normandy invasion and carried on the development of the methods and techniques in this type of forecasting needed to supply the requirements of amphibious operations on the French Coast. The Section operated so successfully that it was sent intact to the Joint Meteorological Centre, Colombo, Ceylon, where it served the Southeast Asia Command and the British East Indies Fleet during 1945.

Using the above example as a basis for reasoning, the writer believes that the organization of an oceanographic forecasting service entirely separate from the weather service already available in a combat theater is a waste of manpower. Although not mentioned in Seiwell's paper, there is a strong need for an extensive observational network to provide sufficient data on which to base and verify forecasts. This network can be readily augmented through the use of the wide-spread, highly trained weather observers already available on land, afloat, and in weather reconnaissance planes. The private and efficient communication network of the weather service also lends itself when needed. And it should always be remembered that forecasts of sea, swell, and surf conditions, if they are to be reliable, must be made at a weather station, as a wave forecast is no better than the wind forecast or diagnosis upon which it is based.

There is, as in the case of oceanographic meteorology, a strong need for joint preparation and presentation of information relating to the oceanographic and hydrographic factors that are either cyclical or slowly transient in nature. These factors include tides, currents, beach slopes, trafficability, and many more. Combination hydrographic-oceanographic specialists could well be fitted into intelligence organizations to acquire and furnish this information as needed, although the necessity for special military oceanographic units is not so evident.

Seiwell's statement that there were disastrous mistakes in early amphibious assaults which caused recognition of an oceanographic concept of amphibious warfare is also open to question. To the best of my recollection, American troops rapidly secured all initial beachheads except one, Tarawa, and the basic causes of that set-back have not, to the best of my knowledge, ever been authoritatively stated.

In conclusion, I should like to reiterate that military oceanography is a broad field of endeavor and cannot be limited to applications for amphibious landings. After all, it would appear most odd to speak of mine oceanography, rescue oceanography, and similar oceanographies when one wanted to discuss the military applications of the science in general terms.

H. R. Seiwell (Woods Hole Oceanographic Institution, Woods Hole Massachusetts, Author's closure)--No one questions the numerous applications of oceanography to military and naval activities of the recent War, but the compilation of such a list is beyond the scope of this paper.

It is to be noted, in dealing with applications of science to military operations, that military ethics and security frequently restrict the information published. Authors with a background of practical war experience hesitate to record results of command decisions, and their contributions may err in a sense of over-responsibility to the policy of national defense.

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

GEOLOGISCHE RUNDSCHAU, Volume 35, Number 1, 1947

The first post-war issue of the Rundschau has been issued and it is a most significant sign of reawakening and the reorganization of scientific life in Germany. Long before the War, the Rundschau was the leading geological journal in Germany and was well known in Europe. Strangely untouched by the decline of scientific work during the last ten or so years it survived all attempts at its extinction.

This first issue contains a mass of welcome information which helps to bridge the gap of the War years. The following is a list of the papers:

BUBNOFF, S. V., Rhythmen, Zyklen and Zeitrechnung in der Geologie, pp. 6-22.
WOLDSTEDT, PAUL, Strahlungskurve von Milankowitch und die Zahl der Eisund Zwischeneiszeiten in Norddeutschland, pp. 24-26.
BEDERKE, E., Über den Wärmehaushalt der Regionalmetamorphose, pp. 26-32.
CLOOS, H., Der Basaltstock des Weilberges im Siebengebirge, pp. 33-35.
KETIN, IHSAN, Kurzer Bericht über die letzten Erdbeben in der Türkei, pp. 36-38.

Following the articles is a list of personal notes on geologists. Organization of new geological surveys in the different Occupational Zones is discussed on pp. 45-48 and supplies very interesting data on personnel at work. On pp. 49-65 is a list of the more important geological papers that have appeared since 1939 and most of which have not yet been received by American libraries. The list comprises the following journals: Badische Geol. Landesanstalt; Reichsamt f. Bodenforschung; Geotektonische Karte von Norddeutschland; Natur und Volk; Senkenbergiana; Glueckauf; Schweizerbarth (incl. Centralblatt); Nova acta Leopoldina; Ber. Freiberger Geol. Ges.; F. Enke, Stuttgart; Naturwissenschaften; Dohrniana; Abh. d. Geol. Inst. Greifswald; Zeitschr. d. Deutschen Geol. Ges.; Deutsche Geol. Landesanstalt; Beitr. z. Geol. Thüringen; Jahreshefte d. Ver. f. Naturkunde Württemberg; Borntraeger, Berlin; Geol. Rundschau vols. 31-34.

The last pages are devoted to a list of members of the Geol. Vereinigung, elections, and similar matter. Papers for the forthcoming issue are listed and the newly elected officers of the society.

It is heartening to see the scientific spirit survive amidst ruins and starvation and it is to be hoped that the effort receives the encouragment it deserves at home and from abroad.

ERNST CLOOS

MULLER, SIEMON WILLIAM, Permafrost or permanently frozen ground, and related engineering problems, J. W. Edwards, Inc., Ann Arbor, Michigan, 231 pp., 1947.

Permafrost, or permanently frozen ground, underlies about one-fifth of the land area of the Earth, varying in thickness up to 400 m. In the Northern Hemisphere, the area includes much of Siberia, most of Alaska, the northern portions of Canada, and most of Greenland. Many of the problems of permafrost areas are those of ground water in the overlying "active" layer, that is, the layer that thaws in summer. Building of a fill may disturb the normal thermal regime and raise the permafrost level under the fill, causing backing up of ground water that may lead to great difficulty and high maintenance or remedial costs. Similarly, stripping the tundra of its insulating layer of moss, sod or peat, may increase the depth of thawing and result in unforeseen difficulties. The construction of a building, especially if heated, may retard the freezing action in the active layer with a consequented concentration of ground water that will lead to icing within and around the structure, resulting in its destruction. The building of a wood fence results in added thawing on the southerly side and less on the northerly side, and may, under certain circumstances, cause icing or other difficulty.

The book is largely a review of Russian literature on the subject, and the results of Russian scientific study and extensive experience are set forth. The principles of permafrost occurrence

and behavior are outlined, and the means of meeting many of the problems are suggested. Invaluable tables of properties of frozen materials including the adhering strength of frozen soils (adfreezing strength), an extensive glossary, and 77 bibliographic items are given.

The author outlines three types of areas of permafrost: (a) Those in which the entire region is frozen, that is, the permafrost is continuous areally; (b) those in which permafrost dominates, but there are islands or strata of unfrozen ground; and (c) those in which the unfrozen ground is dominant but there are islands or strata of permafrost.

He discusses the active and the passive methods of meeting the problems of construction in permafrost areas. In the first, there is the attempt to resist the action of permafrost by strength of structure. This is never successful in areas of continuous permafrost and frequently unsuccessful in others. The forces are too great. Under the passive system, the plan is to meet the problems by an understanding of them through knowledge of the principles, and a study of the areas involved. Areas where the situation is acute should be avoided insofar as possible; otherwise precautionary mitigating measures are to be taken. In general, buildings should have a pier type of foundation which must be anchored by carrying the foundation to some depth into the permafrost to allow the adfreezing strength of the permafrost soil to have dominance over the adfreezing strength of the active layer. This applies to bench marks also.

In a water-supply and distribution system, it is suggested that by laying the pipe at the top of or just above the permafrost layer (that is, at what is usually the bottom of the active layer) and by water temperature observation and control, such a system can be operated successfully. The problems seem insuperable!

The survey becomes a matter of dominant importance (though how a preliminary survey may be undertaken months before the reconnaissance survey is complete, page 165, the reviewer is unable to understand), and the gathering of all the usual data of a survey is augmented by the gathering of the extensive special data relating to the permafrost condition.

This book should be studied by all who plan to engage in any work in the permafrost regions which are ever-increasing in their importance both economically and strategically. It contains a wealth of information, some of which is in need of further development. In common with most books on new subjects, especially those produced under the exigencies of war, the book is not especially well written; it could be much better organized. As a text, it is repetitive, especially in the closing chapter that deals with surveys in which much usual survey material is covered in addition to that relating to the special problem. On the other hand, an attempt to utilize the book as a reference book will result in disappointment, except as preceded by a thorough general reading.

WALDO E. SMITH

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NOTES AND PERSONALIA

NOTES

Corrigenda--October 1947 issue, paper by Albert E. Coldwell, page 750, Table 3, last column. At the heading of the column, beside Wagoner, the footnote entry should be [b], indicating the same day, instead of [a].

December 1947 issue, paper by Ivan Tolstoy, page 830, under "References," the first reference should be BOWIE, WILLIAM instead of HAYFORD, JOHN F.

Display of equipment of Air Weather Service on polar flights--The Air Weather Service of the U. S. Air Force exhibited its meteorological equipment to the delegates of the International Meteorological Organization at Andrews Field on October 4, 1947. It was revealed that regular weather flights are being carried out across the North Pole. One of the exhibits was the B-29 weather plane POLAR QUEEN, a veteran of 11 polar trips. Also shown were photographs of ice conditions in polar waters, taken during the flights.

German Hydrographic Journal--According to a letter from Gunther Boehnecke in Hamburg, the first number of this new journal went to press late in 1947, and it is expected that it will be released early in 1948. The appearance of such a journal has been in prospect for some time. Persons and institutions desiring to receive the publication should write to J. N. Carruthers, Hydrographic Department, Admiralty, Oxgate Lane, Cricklewood, London, N. W. 2, England, in duplicate, indicating what is to be supplied in exchange.

Meeting of the Commission on the Adjustment of European Triangulation--Floyd W. Hough, Chief of the Geodetic Division, Army Map Service, attended a special meeting of the Commission on on the Adjustment of European Triangulation, of which he is a member, in Paris, France, October 15 to 17, 1947. The commission is a special body organized in 1946 as a part of the International Geodetic Association, IUGG, to consider the extension of the Central European Adjustment to cover all Europe. A paper presented by Hough to the Commission included an announcement of the completion in June 1947, of a least-square adjustment of the Central European Net involving an area of 1,100,000 square kilometers. Eleven European nations and the United States were represented at the conference.

Meeting of Mostra Nazionale e Convegno di Cartografia e di Ottica--This Mostra was held in Florence, Italy, October 27 to November 1, 1947; the occasion was a celebration of the 75th Anniversary of the Istituto Geografico Militare. A scientific convention was in session concurrently at which a number of high-grade technical papers were presented on Geodesy, Cartography, and Photogrammetry. Twenty-four nations were represented. Floyd W. Hough, Chief of the Geodetic Division, Army Map Service, was official observer for the United States. The program included an inspection of the Gallileo Factory which has been reconstructed since the War and is now producing optical equipment, survey instruments, and industrial machines. The Mostra comprised a splendid and extensive exhibit of Italian scientific skill involving numerous types of instrumental and mechanical equipment. The new model, IV Stereo Cartographer was demonstrated by its designer, Dr. Santoni. An inspection of the Istituto Geografico Militare revealed that the organization has been reconstituted and is now in operation with a high degree of production.

Return of Task Force 68 from Arctic expedition--Task Force 68, under Robert S. Quackenbush, Captain, U. S. N., returned to the United States in September 1947 after a summer visit to Baffin Bay. The expedition took supplies to the weather station at Thule, Greenland, set up rasonde apparatus at Eureka Sound on Ellesmere Land, and established a central weather station with an air strip on Cornwallis Island. The task force was made up of the ice-breaker, Edisto, the supply-ship Wyandotte, and the former net-layer, Whitewood.

Lecture on establishment of international network of meteorological stations in the Arctic--Charles J. Hubbard, Chief of the Arctic Section, United States Weather Bureau, gave an interesting talk in December 1947 before a group of meteorologists in Washington, D. C. on the work of establishing international meteorological stations in the arctic regions during the summers of 1946 and 1947 by Task Force 68. The three stations established during these expeditions are now in continuous operation in supplying valuable weather data for forecasting purposes. A Danish-U. S. station at Thule is located in Wolstenholm Sound, West Greenland, at 76°36'N, 68°40'W. This is between

Cape York and Whale Sound in the general vicinity of the bases of several of the Peary Arctic expeditions. The second station, established and supplied by air from Thule, is located in Eureka Sound, between Ellesmere Island and Axel Heiberg Land, at 80°13′N, 86°11′W. This region was first discovered by Otto Sverdrup in 1902. The third station is located in Resolute Bay, Cornwallis Island, at 74°41′N, 94°55′W. The last two stations mentioned are sponsored jointly by Canada and the United States. Included were motion pictures in color taken during the 1946 expedition, which was a joint enterprise of the U. S. Navy, Air Force, and Weather Bureau. These included the first motion pictures ever taken of the rugged coast of North Greenland. The pictures covered the entire range of Arctic scenery from the mountainous, glacial coast of Greenland to the flat featureless islands of the Canadian Archipelago. A polar bear hunt with an icebreaker as it crushed its way through the ice of Wellington Channel was an incidental highlight.

Table of provisional earthquake epicenters of the United States Coast and Geodetic Survey, October and November 1947

Date	Time U. T.	Epicenter Lat.	Epicenter Long.	Remarks
1947	h m	°	°	
Oct. 16	2 09.8	64.5 N	148.8 W	About 40 miles southwest of Fairbanks, Alaska; felt; slight property damage
Oct. 20	1 43.3			Aftershock of quake of October 16
Nov. 1	14 58.9	11 S	75 W	About 150 miles northeast of Lima, Peru; 53 reported dead and considerable property damage
Nov. 2	1 32.2	. . .	. . .	Aftershock of quake of November 1
Nov. 2	7 00.3	40 N	127 W	Off Cape Mendocino, California
Nov. 4	0 09.1	43 N	140 E	Off west coast of Hokkaido, Japan
Nov. 7	23 00.5	11 S	75 W	Aftershock of quake of November 1
Nov. 8	5 25.9	7 N	85.5 W	South of Panama
Nov. 12	16 18.9	23 S	171 E	Loyalty Islands
Nov. 14	10 50.5	46 N	143 E	Off northern coast of Hokkaido, Japan
Nov. 17	9 56.5	14 N	45 W	Atlantic Ridge, off northeastern coast of South America
Nov. 20	8 19.3	47 N	153 E	Kurile Islands
Nov. 21	3 54.3	19 N	107 W	About 150 miles off western coast of Mexico
Nov. 21	4 17.7	. . .	. . .	Aftershock of quake at 03^h54^m
Nov. 23	9 46.1	44.8 N	112.0 W	Southwestern Montana; felt in Montana and Idaho
Nov. 25	18 15.1	11 S	75 W	About 150 miles northeast of Lima, Peru

The following shocks had depths greater than normal: Nov. 8, depth about 100 km; Nov. 14, depth about 200 km.

Status of aerial mosaics or photo-maps of the United States--The U. S. Geological Survey has published an index map entitled Aerial Mosaics of the United States. Requests for copies of the map and inquiries relative to it should be addressed to the Map Information Office, U. S. Geological Survey, Washington 25, D. C.

Resumption of publication of Bulletin Géodésique--The Association of Geodesy of the International Union of Geodesy and Geophysics has resumed the publication of Bulletin Géodésique after interruption during the War years. Two issues were published in the last half of 1946 ($1.35) and four quarterly numbers were published in 1947. The calendar year subscription price is $2.65. American subscribers may address the Association in care of AGU.

Japanese hydrographic work--The No. 1 Tenkai Maru, oceanographic vessel of the Japanese Hydrographic Department, was engaged in conducting an oceanographic survey of the waters around the Izu Islands during September 1947.

Return of the Atlantis--The auxiliary ketch Atlantis returned to Woods Hole in September 1947 after a geological expedition to the Mid-Atlantic Ridge, sponsored jointly by the National Geographic Society, Columbia University, and the Woods Hole Oceanographic Institution.

The end of the Kon-Tiki expedition--The balsa raft Kon-Tiki, carrying Thor Heyerdahl and five other observers, was set afloat near Callao, Peru, on April 28, 1947. After drifting 4300 miles with the prevailing wind and the South Equatorial Current, the raft was cast away on Raroia Reef in the Tuamotus on August 7, 1947. It was later salvaged and sent to Norway, and the party returned safely via the United States.

Bear, Bowditch, and Ramapo sold as surplus--The Maritime Commission recently advertised for bids for three former naval vessels that helped make geophysical history. The Bear was built at Dundee, Scotland, in 1874. In 1884 she was acquired by the United States for the relief of the Greely Arctic Expedition. She subsequently was operated on the Bering Sea patrol by the Revenue Cutter Service (now the Coast Guard) until 1926. In 1933 she was the flagship of the second Byrd antarctic expedition under the name Bear of Oakland, and in 1939 she went back to the Antarctic as the Bear for the U. S. Antarctic Service expedition. She served again in Greenland waters in 1941-1942. The Bowditch, which is to be scrapped, was built at Copenhagen, Denmark, in 1929 as the Grace liner Santa Inez. She was commissioned by the Navy in 1940 as a survey ship of 7680 tons. Her last cruise was as headquarters of the Oceanographic Survey Section at Bikini in 1946. The Ramapo, a 17,800-ton tanker built at Newport News in 1929, is the vessel whose lines of soundings across the North Pacific in the period 1925-1935 resulted in vastly increased knowledge of the structure of that ocean.

Action of the International Meteorological Organization--Among the resolutions of the IMO, adopted during the recent sessions in Canada and the United States, were some of special interest to geophysicists relating to certain constants and definitions. They include the composition of dry air, the molecular weights and gas constants of dry air and water vapor, the unit of geopotential (0.98 gdyn m), and the standard pressure surfaces 1000, 850, 700, 500, 300, and 200 mb for weather analysis. The constants and definitions will be published by the IMO.

PERSONALIA

Maurice L. Albertson, Associate Professor of Civil Engineering at Colorado State College, has been given the J. C. Stevens Award of the American Society of Civil Engineers for his paper on Evaporation from a free water surface.

Boris A. Bakhmeteff, Professor of Civil Engineering at Columbia University and Consulting Engineer, has been named co-winner with William Allan of the Norman Medal of the American Society of Civil Engineers for their paper, "The mechanism of energy loss in fluid friction."

Clifford A. Barnes, lately Assistant Chief of the Division of Oceanography, U. S. Hydrographic Office, has been appointed Associate Professor of Oceanography at the University of Washington.

Tor Bergeron, Professor of Meteorology at the University of Uppsala, gave a series of lectures during September 1947 at the central office of the U. S. Weather Bureau in Washington. The lectures covered the background and development of airmass and frontal analysis, the general circulation, and the physics of clouds and precipitation.

Charles J. Fish, Woods Hole Oceanographic Institution, has received word from the Ministère de l'Education Nationale de la République Française of his election as an Officier d'Académie, in recognition of wartime "Services rendus à la Cause française" in operational research, while serving as a Commander in the U. S. Navy in North African waters.

Nathan C. Grover, formerly Chief of the Water Resources Branch of the U. S. Geological Survey, has been given the Annual Achievement Award of the Washington (D. C.) Society of Engineers for his outstanding service with relation to his work in water resources.

A. A. Kalinske, Chief Hydraulic Engineer for Infilco, Inc., has been named the recipient of the Karl Emil Hilgard Prize of the American Society of Civil Engineers for his paper on Conversion of kinetic to potential energy in flow expansions.

Ernest J. Parkin, who has been a mathematician at the U. S. Coast and Geodetic Survey since 1930 (except for three years in the Navy during the War), has resigned to join the staff of the Department of Civil Engineering of Ohio State University.

Roger Revelle was released to inactive duty in the Naval Reserve in December after six and a half years of service. He will continue for the present as Head of the Geophysics Section of the Office of Naval Research.

Paul D. Thomas, Mathematician of the Navy Department, was transferred to the U. S. Coast and Geodetic Survey in July 1947. He will engage in research in the mathematics of map projections.

Theodore von Karman, Director of the Guggenheim Laboratory of Aeronautics, California Institute of Technology, has been named the recipient of the John Fritz Medal for 1947, highest engineering award in the United States.

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of November 28, 1947

The meeting was called to order at 14^h00^m in the Board Room of the National Academy of Sciences-National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by President O. E. Meinzer.

Present--Thirty-six persons were present, namely: L. H. Adams; K. Hilding Beij; Merrill Bernard; Wilbur S. Burbank; Ernst Cloos; Frank L. Culley; H. N. Eaton; R. M. Field; John A. Fleming; W. F. Foshag; R. E. Fuller; R. C. Gibbs; H. W. Hemple; W. G. Hoyt; Earl Ingerson; H. Freeborn Johnston; J. W. Joyce; David G. Knapp; Ray K. Linsley, Jr.; J. Putnam Marble; Martin A. Mason; A. G. McNish; G. Medina; Oscar E. Meinzer; Frank Neumann; C. S. Piggot; F. W. Reichelderfer; Florence Robertson; Irwin Roman; Edward H. Smith; Waldo E. Smith; Harlan T. Stetson; Walter D. Sutcliffe; H. U. Sverdrup; Francis G. Wells; and R. L. Zwemer. The following were excused because of absence from the city or for other reasons: Robert Balk; Arthur Bevan; Perry Byerly; H. D. Harradon; M. King Hubbert; W. D. Lambert; J. B. Macelwane; L. G. Straub; and F. J. Veihmeyer.

Approval of minutes--The minutes of the meeting of May 1, 1947, as published in the August issue of the Transactions, pages 661 to 668, were approved.

General Secretary's Report

Committees of the Union--Because of the elections at the last annual meeting, there have been many changes in the Executive Committee, the Standing Committees, and the Special Committees of the Union. A complete list of the members of all these committees appeared in the Transactions of December 1947 [pp. 964-967].

Office personnel--The staff, working under the direction of the Executive Secretary, includes at the present time Samuel Pepper, Secretary-Stenographer; Margaret E. Lathrop, Editorial Assistant and Electromatic Operator; and Jean Marie Kendrick, Clerk-Typist. Eleanor T. Agar is temporarily employed as Clerk-Typist on contract work to be mentioned later.

Office space--In January 1947, the Union was given office space in the Administration Building of the Carnegie Institution of Washington. Since then an additional room has been temporarily assigned for special work. The office space was assigned with the understanding that the situation would be reviewed at the end of a year to determine the necessity and desirability of the present tenancy of the Union. The officers of the Union will discuss this matter with the Carnegie Institution at an early date.

National Research Council--As in previous years, the Council has granted $400 for the Union's work for the current fiscal year. As new representatives of the Council on the Executive Committee of the Union, Raymund L. Zwemer, new Chairman of the Division of Biology and Agriculture, replaces Robert F. Griggs; and W. A. Noyes, Jr., new Chairman of the Division of Chemistry and Chemical Technology, replaces L. P. Hammett.

Finances--The financial report for the fiscal year 1946-1947 has been audited and approved by the Committee on Audit and published in the Transactions of October 1947 [pp. 816-818]. The net cash balance on hand November 1, 1947 was $12,227.97. As there have been considerable unforeseen increases in both receipts and expenditures, the Budget Committee has been requested to present a revised budget at this meeting.

Our application last spring to the Rockefeller Foundation for an additional grant of $7500 for assistance during the current triennium was declined because of a rule of the Foundation's Board of Trustees that emphasis be placed on work relating to the biological sciences. The authority given at that time to the officers of the Union by the Executive Committee was considered sufficiently broad to justify further efforts to procure assistance. Accordingly, an application has recently been made to the Geological Society of American for a grant of $7500 extending over a three-year period. (The Geological Society acted favorably on this application in late December 1947 as it applied to the first year.

Joint Research and Development Board contract--In June 1947 the Joint Research and Development Board, through C. S. Piggott, Executive Director of the Committee on Geophysical Sciences, requested that the Union compile a list of geophysicists of first-class competence to conduct or direct research in geophysics. A contract for this work was signed late in June 1947. The work is progressing satisfactorily. The Union also will benefit by having this valuable list." The work is being directed by J. A. Fleming and Waldo E. Smith.

Membership--The membership as of November 28 is 3743, including a list (the 17th) just prepared for distribution to the Executive Committee for balloting. In addition, about 50 applications are on hand. A summary covering the period April 27 to November 28, 1947, follows:

Members, April 27, 1947	2966	
Inactive to active status	3	
New members	838	
New corresponding member	1	3808
Active to inactive status	2	
Resignations	32	
Deceased	4	
Dropped	27	65
Members, November 28, 1947		3743

The extraordinary effectiveness of our Membership Committee, under the leadership of Chairman H. Freeborn Johnston, resulting in an average of 120 new members per month over the past seven months, is to be commended in the highest terms.

Herbert E. Merwin has become a life member, effective as of January 1, 1947.

Deaths reported since April 27 are Paul H. Boots, killed in an airplane accident in South America, January 22, 1947; L. Standish Hall, July 5, 1947; Clyde P. Parkinson, May 3, 1947; and Frederick B. Plummer, February 17, 1947.

Publications--The Transactions of June, August, and October have been published since the last meeting of this Committee. (The Transactions for December 1947 has since been distributed also.) Beginning with the August issue it was necessary to increase our order from 3500 to 4500 copies because of the great increase in membership. The stock of Transactions for the first three issues of 1947 was so depleted that new members could not be supplied. Therefore, these new members are being billed from July 1 to December 31 rather than from the beginning of the year as has been the custom. Printing costs, beginning with the December 1947 issue have increased.

International Union of Geodesy and Geophysics--J. W. Joyce has recently been named Secretary of the International Association of Terrestrial Magnetism and Electricity and thus becomes a member of this Committee.

Plans are proceeding for the General Assembly to be held in Oslo, Norway, August 19 to 28, 1948. Formal invitations have not yet been received but word from J. M. Stagg, General Secretary of the International Union, indicates that they are being issued (the invitation from the IUGG arrived late in December 1947). The following have declared their intentions of attending the Assembly: L. H. Adams; Roland F. Beers; K. Hilding Beij; L. V. Berkner; J. A. B. Bjerkness; N. L. Bowen; C. F. Brooks; Robert C. Bundgaard; Chas. R. Burrows; Perry Byerly; Horace R. Byers; J. E. Church; Charles J. Clifford; George B. Cressey; Maurice Ewing; Jno. A. Fleming; Harry M. Fridley; L. C. Graton; Beno Gutenberg; Carl A. Heiland; Henry W. Hemple; Jörgen Holmboe; John M. Ide; Homer Jensen; Arthur J. M. Johnson; H. Freeborn Johnston; H. R. Jordan; J. W. Joyce; Joseph Kaplan; Walter D. Lambert; J. B. Macelwane; Oscar E. Meinzer; G. W. Musgrave; Frank Neumann; B. Perkins, Jr; C. S. Piggot; F. W. Reichelderfer; Elliot B. Roberts; C. G. Rossby; Waldo E. Smith; Edward Steidle; Lorenz G. Straub; H. U. Sverdrup; M. A. Tuve; Harry Wexler; and Charles A. Whitten.

Letters have been sent to university presidents, heads of government and private institutions, and others, calling attention to the Assembly and suggesting the desirability of sending representatives.

Neither the IUGG nor the AGU has any arrangement for providing traveling expenses of delegates. Possibilities that funds may be made available under the Fulbright Act, or from UNESCO, or from other sources, are being investigated. There is also some possibility that representatives

of various Federal agencies may be furnished air transportation by the Army or the Navy. It is very unlikely that any funds will be available from the National Research Council.

Meetings--A New England Regional Meeting was held September 17 to 19; on the 17 at Wesleyan University, Middletown, Connecticut; on the 18 both at the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, and at Harvard University, Cambridge, Massachusetts; and on the 19 again in Cambridge. The Meeting was an outstanding success for which our thanks are due to the Committee under the Chairmanship of Richard M. Field.

The Washington Group of the Section of Hydrology met on November 5 and heard a talk by Gerard H. Matthes on "Preservation of our Rivers." The talk was well received and elicited considerable discussion.

Plans for a South Pacific Regional Meeting in February 1948, are developing rapidly. Originally the Section of Hydrology, through its Regional Committee under the Chairmanship of F. J. Veihmeyer, scheduled a meeting for February 13 and 14 at Berkeley, California. In line with the action of the Executive Committee on May 1, 1947, Vice-President Sverdrup investigated the possibilities of broadening the scope of this meeting to include the whole Union, and as a result of the favorable response the following general committee on arrangements has been appointed: George F. McEwen (Chairman), R. D. Horne (Geodesy), Perry Byerley (Seismology), Woodrow C. Jacobs (Meteorology), J. Jay Jakosky (Terrestrial Magnetism and Electricity), O. W. Swainson (Oceanography), Howel Williams (Volcanology), Frank J. Veihmeyer (Hydrology), Beno Gutenberg and Walter C. Lowdermilk (members at large). Chairman McEwen appointed J. W. Johson as Chairman of the Committee on Local Arrangements.

Regionalization--The Section of Hydrology feels that the time is ripe for regionalization of the Section even if the Union as a whole is not prepared to do so. The Executive Committee of the Section has referred a report on regionalization to this Committee which will be presented later by Merrill Bernard.

National Roster--We are pleased to report that the booklet entitled "Geophysics as a Profession" was published by the National Roster late last spring and copies have been given rather wide distribution. They are available through the office of the Union, the National Roster, and the Government Printing Office.

Civil Service Commission--In connection with the setting up of a classification relating to the grouping of the physical sciences by the Civil Service Commission, the Union received in August an invitation to discuss the plans while they were still in a formative status. After discussion with various members of the Executive Committee and others, a reply was prepared by the Executive Secretary.

Inter-Society Committee on Science-Foundation Legislation--As previously reported the American Association for the Advancement of Science set up this Inter-Society Committee. The Union was invited to appoint two representatives on this Committee and Past-President Adams appointed the Vice-President and the General Secretary. Certain expenses have been incurred in this connection and participating societies have been requested to contribute.

Cooperation with the American Standards Association Committee Z38on Photography--Fred Anderegg has been appointed our representative on this Committee which has been quite active in the formulation of standards. Notices will be published in the Transactions from time to time, and all members who are interested are urged to transmit their suggestions and recommendations to our representative.

Miscellaneous--In response to a formal invitation, Joe Webb Peoples of Wesleyan University was appointed representative of the Union at the Centennial Celebration of the founding of the Sheffield Scientific School of Yale University in October.

More recently, President Meinzer appointed M. King Hubbert, President of the Section of Tectonophysics, as representative of the Union at the dedicatory ceremonies of the new laboratory of the Shell Oil Company in Houston, Texas.

In July a letter was received from William F. Tanner, Professor of Geology at Oklahoma Baptist University, Shawnee, Oklahoma, suggesting that sedimentation covers such a broad field including historial sedimentation of special interest to geologists, current sedimentation of special interest to hydrologists, airborne deposits of special interest to meteorologists, and sedimentation in ocean basins, that a new section of sedimentation or sedimentology should be established in the Union. Action at this Meeting is requested.

Following are extracts from three of the many interesting letters received during recent months from foreign colleagues.

From Dr. Pentti Eskola of Finland:

"I have to thank you very much for your letter of June 20, 1947, in which you communicate to me that I have been elected Corresponding Member in American Geophysican Union. ... I feel this election as an outstanding honor and I beg you kindly to express my great gratitude to the Executive Committee of the Union."

From Dr. Henrik Renquist (President of the Commission on Limnology) of Finland:

"Today I have received the Transactions of the American Geophysical Union and it was really a grand gift. I have been the whole day absorbed in this literature... you cannot think how welcome these papers are. On a single day the windows are thrown open, the windows looking at the intense activity of American Science and its great achievements. Thank you very much indeed. This day I have gathered more information in hydrology than during long periods of isolation."

From Prof. ir. J. Th. Thijsse (Secretary of Netherlands Section of Hydrology) of the Netherlands:

"Some time ago our laboratory received... the Transactions. We thank you very much for sending them. They contain a multitude of information... of the utmost importance to us. We should appreciate very much to receive future issues... Of course everything that will be issued in the future [by us] will be sent to you."

Inter-Society Committee on Science-Foundation Legislation--With regard to an AGU contribution to the expenses of this Committee, R. L. Zwemer advised that the National Research Council does not attempt to influence legislation and does not give financial support to such activity. No action was taken, but the prevalent feeling seemed to be that we should pursue the policy of our parent organization.

Sedimentation--The suggestion that a Section of Sedimentation be established was discussed at length, and action was taken to refer this to the Section of Hydrology, for consideration by that Section's Committee on Sedimentation and Dynamics of Streams. That Committee should consult with officers of, and individuals affiliated with, other sections, most notably Meteorology and Oceanography, having an interest in the broad field of sedimentation. The general feeling was expressed, however, that a Union Committee on Sedimentation might be more appropriate than a section, it being a process involved in the fields of several of the existing sections.

Reports of Standing Committees

Membership--Chairman Johnston reported briefly on the activity of the Committee, and closed with an appeal for the names of qualified prospects.

Chairman Roman of the Subcommittee on Corporation Membership reported briefly on the plans of this Committee to secure corporation members.

Meetings and regionalization--Chairman Marble recommended that the plan to hold a South Pacific Meeting of the Union on or about February 13 and 14, 1948 be formally approved. This was done.

He offered alternate plans for the Twenty-Ninth Annual Meeting in Washington, D. C.: The first to hold the Meeting in three rather widely separated auditoria on April 21 to 23, 1948; the other to hold the meeting in the two more closely situated auditoria on April 20 to 23, 1948. The first plan was approved. He pointed out that the Union has now outgrown room-sized meeting places, and yet does not require large auditoria. Those of intermediate size are rather difficult to secure at the time desired and in the most convenient locations.

He mentioned that plans are under way to include a general symposium on the Earth's crust in the 1948 program and that Merle A. Tuve, Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has the plans for this symposium in hand. Symposia in geochemistry, sedimentation, and other broad subjects are tentatively planned for later meetings.

As the matter of regional meetings and regionalization is now in the hands of the Committee, Merrill Bernard, of the Committee on Regionalization for the Section of Hydrology, presented his report that had been approved by the Executive Committee of the Section of Hydrology and referred to the Executive Committee of the Union. This report is presented as Appendix 1. The report was referred to the Committee on Meetings for consideration and subsequent report.

J. A. Fleming was requested to give further information regarding the General Assembly of the IUGG, to be held in Oslo, Norway, August 19 to 28, 1948. He outlined the procedure with regard to the designation of delegates, their recommendation by AGU to the National Research Council which makes the appointments. In the discussion that followed, it was pointed out that the voting representatives to the IUGG and the Associations are, by custom, selected by the delegates, though the Executive Committee of the Union can exercise this function if it desires. J. A. Fleming mentioned also the necessity for early planning of the trip on the part of persons attending, emphasizing that return passage should be assured to avoid being stranded.

With regard to IUGG relationships to UNESCO, he pointed out that the UNESCO had made about $25,000 available to IUGG for 1947, and felt that similar provisions might be expected in the future.

C. S. Piggot, Executive Secretary of the Committee on the Geophysical Sciences, Research and Development Board, brought out the fact that many of the members of their panels are members and officers of AGU, and expressed the thought that a dual purpose and a common objective could be attained by designating such persons as delegates from our parent organization, the National Research Council, and as representatives from the various geophysical panels of the Board. He believed that Army or Navy surface or air transportation might be available to transport such persons to and from the Meeting. He further mentioned the desirability of having a strong delegation from among the scientists of the Board and its panels.

H. U. Sverdrup mentioned that he had investigated the possibilities of securing funds for travel under the Fulbright Act through the Norewgian Embassy. No definite word is yet available in this regard. He mentioned also the possibilities of securing such funds through UNESCO should be thoroughly investigated.

Budget--President Meinzer, in introducing Chairman Eaton, stated that he had fulfilled the mandate of the Executive Committee at its meeting on May 1, 1947, and instructed the Committee on Budget that it should also exercise the broad functions of a Ways and Means Committee. He mentioned that these instructions would stand, unless other instructions were given by the Executive Committee.

Chairman Eaton outlined suggested budget changes resulting from the Committee's studies (see Appendix 2). These changes were discussed and approved. He mentioned further studies that his Committee has in progress with regard to Ways and Means and plans to present a report on this study at the next meeting of the Executive Committee.

Audit--Chairman McNish reported that the Committee had found the accounts and financial records of the Union in good order as reported in the Transactions in October 1947. [pp. 816-818].

Reports of Special Committees

Cooperation with International Commission for Study of Tidal Waves--Chairman Mason reported that his Committee is investigating the present status of the International Commission, but he feels that there is important work for this Committee to do regardless of the status of the International Commission.

Surveys and maps--Chairman Medina reported that this Committee has gotten under way, and outlined briefly a five-point program that the Committee plans to pursue.

Affiliation with the American Geological Institute--In the absence of Chairman Thom, General Secretary Beij presented a communication from him indicating his review of action taken by the Committee on Organization at the meeting on October 24, 1947. At that meeting the Committee took steps to recommend to the eleven related societies to set up the Institute in the framework of the Division of Geology and Geography of the National Research Council to which Thom added his personal endorsement, awaiting action by his Committee. No formal action was taken, as a formal invitation to affiliate had not arrived.

New England Meeting and International Conference on the Earth Sciences and Civilization--Chairman Field reported on both of these meetings, the first of which is reported in the issue of the Transactions of December 1947 [p. 967].

Section Matters

Hydrology--W. G. Hoyt, representative for L. G. Straub, President of the Section, reported that all research and other committees have been formed, and work is proceeding. He added further that the Section would await with great interest the development of the idea of regionalization, referred to the Union's Committee on Meetings.

New Business

Earl Ingerson suggested that in connection with the development of regionalization and regional meetings we should take steps also to develop joint meetings with, for example, the Geological Society of America. The suggestion was well received but no formal action was considered necessary at this time.

Adjournment--The meeting adjourned at 17^h40^m.

K. Hilding Beij, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--MEMORANDUM TO LORENZ STRAUB, PRESIDENT, SECTION OF HYDROLOGY, AGU, REGARDING REGIONALIZATION

(Referred to the Executive Committee of the Union by the Executive Committee of the Section of Hydrology)

The following summary report is made in accordance with your instructions and with the approval of F. J. Veihmeyer, Chairman, Subcommittee on Regionalization.

Background--The American Geophysical Union of the National Research Council is comprised of Sections representing the natural sciences. The Sections, enjoying a high degree of autonomy, are administered by the officers of the Union through an Executive Committee and a Secretariat. The organizational structure is designed to remove or reduce the distractions of administrative routine, professional employment problems, and social activities and to create an environment in which the strictly scientific aspects of geophysics can receive the first-hand attention of the membership. It can be said the Union has had more than passing success in maintaining this feature of its organization.

The Union accomplishes the dissemination of scientific knowledge through (1) periodically published Transactions, (2) the activities of its permanent research committees, (3) an Annual Meeting in Washington, D. C., (4) occasional meetings held in other cities. The Transactions are rapidly developing into a major asset and are acquiring a reputation as a source of scientific information of the first order. The permanent research committees are groupings of those members whose enthusiasms and devotion to cause overcome the discouragements inherent in all unfinanced programs. The Washington Annual Meeting has been sustained by the relatively small group of scientists whose residence has made it possible to attend them. For a number of years, member groups in other parts of the country have held meetings which have come to be called "Regional Meetings." It is this development that has pointed to the necessity to consider and, if found desirable, to act upon a plan to regionalize all activities of the Union.

Purposes to be served by regionalization--It is essential that the scientific endeavors of the Union remain dominant and free from the competition of excessive administrative and organizational demands. To maintain this safeguard, the expansion from a highly centralized operation in Washington to one which is to be distributed over the whole of the country must be kept in the simplest terms of field organization. It is believed this can be done if the problems as we now face them are kept in view. These are:

(1) It is not possible for the greater portion of the membership to attend the Annual Meeting in Washington. Recent campaigns have extended the membership into every state. The new member, not appreciating the Washington traditions that have even now established themselves, or having the associations enjoyed by the member living within travel range of Washington, will expect more than the Union's literature if his continuing interest and support are insured. It is generally recognized that "too much Washington is not conducive to the growth of a national association."

(2) A continuing problem in the Union is to prevent the Sections and the Research Committees within the Sections from becoming self sufficient, compartmentalized units. At present, this prevented, presumably, by encouraging collaboration between research committees and developing joint meetings of the Sections. The difficulties of effactuating these coordinative efforts in or from Washington have already been experienced.

(3) It is certain that membership groups throughout the country will continue to organize meetings by sections or combination of sections. There is evidence that, because of the absence of field organization, the meetings are often less well managed than they should be. A continuing regional organization would provide the machinery for the conduct of such meetings.

(4) Questionnaires and membership application blanks emanating from Washington are anathema to the average American. Despite the success the Union has had in building its membership to present proportions, future expansion will require some degree of localized activity which regionalization can provide.

A suggested plan for regionalization--The following steps toward regionalization are proposed:

(1) A statistical analysis by the Office of the Secretary to determine

(a) The geographical distribution of the present and potential membership of the Union.

(b) The location of regional boundaries so placed that the membership within any region travels the shortest distance to those cities which must be utilized as meeting places.

(2) The President of the Union, after collaborating with the Presidents of the Sections, to appoint a representative in each Section in each of the designated regions to constitute a Regional Committee.

(3) Each regional committee to select its own chairman.

(4) Each section representative to collaborate with the chairman of the permanent research committees in his section to determine in what ways he, the regional representative, can be helpful in furthering the programs of the respective research committees.

(5) The enactment of such rules and by-laws as are necessary to:

(a) Clarify the functions of the Regional Committees.

(b) Authorize the Committees to organize and conduct section or joint section meetings.

(c) Place restraint on the Regional Committees to prevent over-organization and regional "empire building."

You will recall, at the recent meeting of the Executive Committee of the Section of Hydrology, it was decided that I formalize my oral report of the Subcommittee on Regionalization and that the report be forwarded to the Executive Committee of the Union for such value as it might have in bringing about the regionalization of the entire Union. However, it was understood that should the Union as a whole decide not to undertake regionalization at this time, the Section of Hydrology would proceed to consider a plan of regionalization designed to meet its own needs. It is the opinion of your Subcommittee that the problem could be met more effectively if the former course, that is, the regionalization of the entire Union, were followed.

Merrill Bernard, Member, Subcommittee
on Regionalization, Section of Hydrology

APPENDIX 2--REPORT OF THE COMMITTEE ON BUDGET

H. N. Eaton, Chairman

Jno. A. Fleming Roy W. Goranson - Nathan C. Grover

The Committee on Budget of the American Geophysical Union has conferred with the Executive Secretary and the General Secretary of the Union regarding the changes for which provision

should be made in the budget because of changes in the needs and in the income of the Union and recommends the following:

		Decrease	Increase
Estimated changes in expenditures:			
Transactions:			
(a) Revise previous estimate			300.00
(b) Increased number of copies			700.00
(c) Increased cost of reproduction			500.00
Reprints: Increase in number and cost			100.00
List of members: Omit this year		$ 750.00	
Bibliography of Hydrology: Will be published elsewhere		700.00	
Membership Committee: Increase			1,000.00
Travel: Increase			200.00
Stationery and miscellaneous			200.00
Bills payable: As of June 30, 1948			920.00
	Totals	$1,450.00	$3,920.00
	Net increase		$2,470.00
Estimated changes in income and assets			
Regular Union funds as of July 1, 1947:			
Estimated to actual			$1,943.39
Dues from increased membership			2,000.00
Increased sales of reprints			100.00
Bills receivable:			
Estimated to actual		$ 51.53	
	Totals	$ 51.53	$4,043.39
	Net increase		$3,991.86

The estimated change in income and assets exceeds the estimated increase in expenditures by $1521.86.

The above recommended changes have been considered carefully and in detail, and the Committee believes that the estimated amounts are conservative.

UNION ACTIVITIES

Committee on Membership--Robert S. Arthur, Scripps Institution of Oceanography, has been appointed a member of the Committee on Membership, taking the place of Walter H. Munk.

American Standards Association--Fred Anderegg, AGU, representative on the Committee on Photography, Z38, of the American Standards Association advises that the latest standard approved by the Association is American Standard Practice for Photographic Processing Manipulation of Films and Plates. This Standard, number Z38. 8.3-1947, dated October 7, 1947, applies to operations concerned with the processing of silver halide photographic layers involving developing, rinsing, fixing, washing and drying of films and plates, excluding reversal and color processes.

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION, OCTOBER 21, 1947 TO JANUARY 10, 1948

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SPECIAL ANNOUNCEMENTS

Twenty-Ninth Annual Meeting, Washington, D. C., April 21 to 23, 1948--The Twenty-Ninth Annual Meeting of the American Geophysical Union will be held in Washington, D. C., April 21 to 23, 1948. Those desiring to present papers should refer to the Special Announcement in the issue of the Transactions for December 1947, page 972. Titles and abstracts should be in the office by late February, 1948, but those received through the first week in March can probably still be placed on the program. Advice must be given concerning the time (most papers are allowed from 10 to 20 minutes) and projection equipment required. If a paper is written in collaboration, indicate by whom it is to be given. Arrangements can be made for the presentation of papers by authors who are unable to attend the meetings.

Complete manuscripts of papers should be forwarded in triplicate (double-spaced, 16 lb paper) by the end of March, 1948, in order that news releases may be prepared. Papers for publication in the Transactions are subject to acceptance by the Editorial and Publication Committee, and are published for each section approximately in the order received.

An author owes it to his audience that his paper, presented orally, be prepared for such presentation. Ordinarily, complicated mathematical presentations should be reserved for publication. Care should be taken to stay within prescribed time-limits, and to avoid encroachment on the time allotted for discussion or for succeeding presentations. Following the oral presentation of a paper, there will normally be an opportunity for discussion from the floor. Discussors are invited to prepare their comments for consideration for publication with the paper.

The main registration and information desk will be near the entrance to the Auditorium of the National Museum. Others, however, will be maintained at the Departmental Auditorium and at the Auditorium of the National Academy of Sciences-National Research Council Building. Make hotel reservations early, as late April is a busy season in Washington.

A program giving dates, hours, and meeting places will be mailed to each member about two weeks in advance of the meeting. Be on the lookout for yours.

It is still not too late to send in suggestions for the meeting. These should be sent to the office of AGU, or directly to Dr. J. P. Marble, Chairman of the Committee on Meetings, AGU, U. S. National Museum, Washington 25, D. C.

General Assembly of the International Union of Geodesy and Geophysics--The Eighth General Assembly of the IUGG and its Associations will be held in Oslo, Norway, August 19 to 28, 1948. Word has been received from more than 50 who plan to attend from the United States. The final list of delegates and guests will be made up by mid-April and any who plan to go and have not yet advised the AGU office should do so immediately.

Reservations for the outgoing and the return trip should be made promptly. In no case should one embark without being assured of return passage to avoid the possibility of being stranded. See your local travel agent. The AGU office will assist and advise any who request such information, but cannot book passage. It is not desirable to book passage through more than one agent, as cancellation is being made of all passage in which duplication is detected.

The agenda of the meetings of the Union and of the Associations are rapidly being established. All resolutions and other items for the agenda must be mailed at once to the office of AGU. Abstracts of papers should be sent to the office of AGU promptly for transmission to Association Secretaries or their American representatives. Abstracts should not be more than 1000 words. A preliminary program will be issued in the late spring, and abstracts will be printed and circularized in advance of the meetings. In general, unabridged papers, and an outline of discussions will be published after the Assembly, provided all material is handed in at the beginning of the Assembly. Proposals from individuals or groups for coordinated research on an international basis will be welcomed, but must be sent at once to the office of AGU.

Back issues of the Transactions--The office of AGU has frequent inquiries concerning the availability of back Transactions. The last published list appeared on closing pages of Part 6 of the Transactions of 1944, following page 1065. This list indicates those no longer available at that time. Since then, the following have ceased to be available: Part I, 1934; Part II, 1935; Parts I and II, 1937; Part I, 1939; Parts I and II, 1943; and Parts III and IV, 1944.

All three numbers of the Transactions of 1945 are still available at $1.50 per copy, or $3.75 for the set; all six numbers are available for 1946 at $1.50 per copy or $7.50 for the set; for 1947, only the last three numbers are available at a price of $1.50 per copy or $3.75 for the set. An occasional copy of the issue of June 1947 is also still available at a price of $1.50 per copy. All prices shown are for non-members. To members ordering Transactions on their own account, there is a discount of one-third.

TRANSACTIONS
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GEOPHYSICS IN WAR AND PEACE

B. Gutenberg

Abstract

(Balch Graduate School of the Geological Sciences, Contribution No. 419)

Geophysics is the science dealing with physical processes or facts related to the Earth, to its solid body as well as to the water and the atmosphere. It may be divided into general geophysics, the study of geophysical problems for reasons primarily scientific, and applied geophysics which is concerned with problems of economic or military importance [see "References" at end of abstract, GUTENBERG, 1937].

As geophysicists investigate problems covering the whole Earth, international cooperation is highly important. On the other hand, cooperation with other sciences, especially geology, geochemistry, and astronomy, is necessary. Geodesy is closely related to geophysics, and sometimes is considered a part of it or combined with it in "geonomy." Knowledge of the fundamental problems of physics is required of a geophysicist. Details depend on the particular problems; the theory of elastic waves plays an important role in many investigations; the theory of gravitation, electricity, magnetism, optics, and other studies in other fields. In applied geophysics, familiarity with fundamental problems of electrical engineering (electronic devices in instruments) is essential.

Geophysics started relatively late as a separate science; many of its fields were considered a part of other sciences, especially geology. However it is of little importance under which auspices geophysical research is being done, as long as results are obtained. In many instances, study of geophysical problems requires cooperation of various sciences. For example, in the investigation of an earthquake, the process itself and the propagation of the waves is a geophysical problem; the determination of the faults, their age, or the displacements during the past must be investigated by a geologist; displacements before, during, and after the earthquake have to be found by the geodesist; stress and strain in the various parts of a building should be studied by the engineer. Other examples could be cited.

It must always be considered that there is only one Earth; consequently in investigations concerning the Earth or parts of it, theories of geology, geophysics of the solid Earth, oceanography, physics of the atmosphere, or astronomy must not contradict each other or observations in those various fields. The close relationship between gravity anomalies, ocean deeps, volcanoes, earthquakes, and the location of the andesite line along the boundary of the Pacific Basin, is an example of the problems which require cooperation among various specialists. Another is furnished by the correlation between solar activity, auroras, changes in the magnetic field of the Earth, in radio-wave propagation, and in the ionosphere. A frequently overlooked field of necessitous cooperation is that dealing with the effect of geophysical processes on life. This not only includes bioclimatology and paleogeography, both important for the investigation of the climates of the past, but also problems such as daily, annual, and other cycles in life; the appearance of certain animals at the surface of the ocean during a given phase of the moon for mating; orientation during migration of birds.

In many instances, investigations in general geophysics have later found practical applications in peace and war, such as the study of microseisms, the propagation of elastic waves (sound waves) in the solid Earth as well as in the ocean and in the atmosphere. Practically all geophysical prospecting for water, oil, and minerals was originally based on existing methods and results of the corresponding fields in general geophysics.

As stated, geophysics requires international cooperation. This led to international organizations during the earliest history of geophysical science, earlier than in most other sciences and with excellent cooperation, strengthening the idea of "one world." However when a war was forced upon a country, geophysics always played an important role, not only in forecasting weather, river, and ocean conditions, but also in construction of devices in connection with transportation by air and water, and in various other fields, not always of a geophysical nature, but for which the specific

training of a geophysicist furnished the essential preparation. However geophysicists, probably more than people in general, are working for peaceful international cooperation, by exchange of publications as well as by international meetings. This results in a better understanding of the physical facts and processes concerning the Earth as a whole as well as parts of it, in the decrease of damage and loss of life, for example by floods, storms, earthquakes, and volcanoes, and in a better utilization of natural energies.

Reference

GUTENBERG, B., Geophysics as a science, Geophys., v. 2, pp. 185-187, 1937.

California Institute of Technology,
Pasadena, California

(Abstract received November 12, 1947; presented at the International Conference on the Earth Sciences and Civilization, South Duxbury, Massachusetts, September 22, 1947; open for formal discussion until September 1, 1948.)

A METHOD OF SIMULTANEOUS SOLUTION OF A SYSTEM OF OBSERVATION AND CONDITION EQUATIONS

Joseph L. Stearn and Norman F. Braaten

Abstract--The purpose of this paper is to deduce a new method for obtaining a solution to a system of observation equations which is constrained by a number of conditions. A most general case in least-squares theory is first formulated followed by an actual problem in geodesy. The results of this paper lead to the conclusion that the method is very well adapted to adjustment problems in area triangulation inasmuch as it is both efficient and flexible.

Introduction--The study of a procedure for handling a large set of observation equations with a small number of imposed conditions arose in connection with the least-squares adjustment of an area of triangulation in which observation equations were used in place of the conventional angle and side equations of an arc of triangulation together with a rigorous length and/or Laplace azimuth condition.

Throughout this paper the Gaussian notation generally found in the least-squares theory will be employed, so that square brackets denote summation, [aa] denoting the sum of the products of the coefficients of the first unknown x_1 by these same coefficients, [bc] denoting the sum of the products of the coefficients of the first unknown x_1 by the coefficients of the second unknown y_1, and so forth, as shown below.

$$[aa] = a_1 a_1 + a_2 a_2 + \ldots + a_r a_r$$

$$[bc] = b_1 c_1 + b_2 c_2 + \ldots + b_r c_r$$

$$[cN] = c_1 N_1 + c_2 N_2 + \ldots + c_r N_r$$

$$[bb\ 1] = [bb] - [ab][ab]/[aa]$$

In this paper the problem and solution will first be indicated in general terms, then a specific problem in triangulation will be considered, where the unknowns of the observation equations represent the shifts in latitude and longitude of the triangulation stations (x_2 and y_2 representing these shifts for station 2); the coefficients are functions of the geographic positions of the stations; the N's are absolute terms representing differences between computed and observed azimuths; the v's are corrections to be determined and applied to the observations; and the unknowns in the condition equation are written in the standard form to satisfy the extra length condition.

General problem--Given r observation equations in 2u unknowns

$$\begin{aligned}
v_1 &= a_1x_1 + b_1y_1 + c_1x_2 + d_1y_2 + \ldots + s_1x_u + t_1y_u + N_1 \\
v_2 &= a_2x_1 + b_2y_1 + c_2x_2 + d_2y_2 + \ldots + s_2x_u + t_2y_u + N_2 \\
v_3 &= a_3x_1 + b_3y_1 + c_3x_2 + d_3y_2 + \ldots + s_3x_u + t_3y_u + N_3 \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
v_r &= a_rx_1 + b_ry_1 + c_rx_2 + d_ry_2 + \ldots + s_rx_u + t_ry_u + N_r
\end{aligned}$$

and k condition equations

$$\begin{aligned}
\ell_1v_1 + \ell_2v_2 + \ldots + \eta_1 &= 0 \\
m_1v_1 + m_2v_2 + \ldots + \eta_2 &= 0 \\
&\ldots\ldots\ldots\ldots\ldots \\
k_1v_1 + k_2v_2 + \ldots + \eta_k &= 0
\end{aligned}$$

It is required that [vv] be minimized subject to the k given conditions. $U = v_1^2 + v_r^2 + \ldots + v_r^2$

$$
\begin{aligned}
&+ 2C_1\ell_1(a_1x_1 + b_1y_1 + c_1x_2 + d_1y_2 + \ldots + s_1x_u + t_1y_u + N_1)\\
&+ 2C_1\ell_2(a_2x_1 + b_2y_1 + c_2x_2 + d_2y_2 + \ldots + s_2x_u + t_2y_u + N_2) + \ldots\\
&+ 2C_1\eta_1\\
&+ 2C_2m_1(a_1x_1 + b_1y_1 + c_1x_2 + d_1y_2 + \ldots + s_1x_u + t_1y_u + N_1)\\
&+ 2C_2m_2(a_2x_1 + b_2y_1 + c_2x_2 + d_2y_2 + \ldots + s_2x_u + t_2y_u + N_2) + \ldots\\
&+ 2C_2\eta_2 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
&+ 2C_kk_1(a_1x_1 + b_1y_1 + c_1x_2 + d_1y_2 + \ldots + s_1x_u + t_1y_u + \ldots + N_1)\\
&+ 2C_kk_2(a_2x_1 + b_2y_1 + c_2x_2 + d_2y_2 + \ldots + s_2x_u + t_2y_u + \ldots + N_2) + \ldots\\
&+ 2C_k\eta_k
\end{aligned}
$$

where $C_1, C_2, \ldots C_k$ are the Lagrangian multipliers.

Taking partial derivatives of U with respect to each of the unknowns (substituting for v_i^2, where $i = 1, 2, \ldots r$, the squares of the right hand sides of the given observation equations) and equating them to zero gives

$$(1/2)\partial U/\partial x_1 = [aa]x_1 + [ab]y_1 + [ac]x_2 + [ad]y_2 + \ldots + [as]x_u + [at]y_u + C_1[a\ell] + C_2[am] + \ldots + C_k[ak] + [aN] = 0 \ldots\ldots\ldots (1)$$

$$(1/2)\partial U/\partial y_1 = [ab]x_1 + [bb]y_1 + [bc]x_2 + [bd]y_2 + \ldots + [bs]x_u + [bt]y_u + C_1[b\ell] + C_2[bm] + \ldots + C_k[bk] + [bN] = 0 \ldots\ldots\ldots (2)$$

$$(1/2)\partial U/\partial x_2 = [ac]x_1 + [bc]y_1 + [cc]x_2 + [cd]y_2 + \ldots + [cs]x_u + [ct]y_u + C_1[c\ell] + C_2[cm] + \ldots + C_k[ck] + [cN] = 0 \ldots\ldots\ldots (3)$$

$$(1/2)\partial U/\partial y_2 = [ad]x_1 + [bd]y_1 + [cd]x_2 + [dd]y_2 + \ldots + [ds]x_u + [dt]y_u + C_1[d\ell] + C_2[dm] + \ldots + C_k[dk] + [dN] = 0 \ldots\ldots\ldots (4)$$

. . . . . .

$$(1/2)\partial U/\partial x_u = [as]x_1 + [bs]y_1 + [cs]x_2 + [ds]y_2 + \ldots + [ss]x_u + [st]y_u + C_1[s\ell] + C_2[sm] + \ldots + C_k[sk] + [sN] = 0 \ldots\ldots (2u-1)$$

$$(1/2)\partial U/\partial y_u = [at]x_1 + [bt]y_1 + [ct]x_2 + [dt]y_2 + \ldots + [st]x_u + [tt]y_u + C_1[t\ell] + C_2[tm] + \ldots + C_k[tk] + [tN] = 0 \ldots\ldots\ldots (2u)$$

We have a set of 2u equations containing 2u unknowns and k Lagrangian multipliers. Putting the given condition equations in terms of the unknowns x_1 and y_1 gives

$$[a\ell]x_1 + [b\ell]y_1 + [c\ell]x_2 + [d\ell]y_2 + \ldots + [s\ell]x_u + [t\ell]y_u + [\ell N] + \eta_1 = 0 \ldots (2u + 1)$$

$$[am]x_1 + [bm]y_1 + [cm]x_2 + [dm]y_2 + \ldots + [sm]x_u + [tm]y_u + [mN] + \eta_2 = 0 \ldots (2u + 2)$$

. . . . . .

$$[ak]x_1 + [bk]y_1 + [ck]x_2 + [dk]y_2 + \ldots + [sk]x_u + [tk]y_u + [kN] + \eta_k = 0 \ldots (2u + k)$$

We now have a system of (2u + k) normal equations which can be solved for all the unknowns. This system of normal equations differs from the ordinary system in that the elements $[\ell\ell]$, $[\ell m]$, . . . $[\ell k]$, [mm], . . . [mk], . . . [kk] are zero.

These equations may be solved by the method of substitution and elimination or by determinants. However, it is desirable to have a systematic and practical method which can be adapted to machine calculation. Such a method is the Doolittle solution of a set of normal equations [see "References" at end of paper, ADAMS, 1915]. Inasmuch as the diagonal elements $[\ell\ell]$, [mm], . . . [kk] are zero, it is necessary that the equations (2u + 1), . . . (2u + k) be solved following equations (1), . . . (2u), in order to avoid the case of indeterminacy.

Substitution of the unknowns in the equations (1), (2), (3), (4), . . . (2u-1), (2u), (2u+1), (2u+2), . . . (2u+k) constitutes a very useful check on the values of the unknowns which are calculated in the "back solution."

The method outlined in this paper for solving simultaneously a set of observation equations and condition equations to yield a set of residuals, the sum of the squares of which is a minimum, is a very useful tool in geodetic work. For example, in the adjustment of area triangulation by the method of variation of geographic coordinates we may have several hundred observation equations and a small number of condition equations. These condition equations occur for Laplace azimuths and base lines.

Table 1 shows the equations written in tabular form with the coefficients of the observation equations in rows and the coefficients of the condition equations in columns. The normal equations in Table 2, which are (1), (2), . . . (2u + k), need not be derived by differentiation, but may be formed from Table 1 as follows: The coefficients and constant terms of the first 2u normal equations are derived in the same way that they would be if Table 1 were an ordinary set of correlates, including the sums of products of observation coefficients and condition coefficients. The diagonal coefficients (and all terms to the right except the constant terms) of (2u + 1), . . . (2u + k) are zeros. The constant terms of these equations are formed by the sums of the products of the elements of the C columns by the elements of the N columns, remembering to add to these sums the respective η's (closures) of the condition equations.

Table 1--Observation and condition equations

Observation coefficients								Condition coefficients				Observation absolute terms
..	x_1	y_1	x_2	y_2	. . .	x_u	y_u	C_1	C_2	. . .	C_k	N
v_1	a_1	b_1	c_1	d_1	. . .	s_1	t_1	ℓ_1	m_1	. . .	k_1	N_1
v_2	a_2	b_2	c_2	d_2	. . .	s_2	t_2	ℓ_2	m_2	. . .	k_2	N_2
v_3	a_3	b_3	c_3	d_3	. . .	s_3	t_3	..	..	..	..	N_3
. .	. .	. .	. .	. .	. . .	. .	. .	..	..	..	..	..
v_r	a_r	b_r	c_r	d_r	. . .	s_r	t_r	..	..	..	..	N_r
Condition constants								η_1	η_2		η_k	

Table 2--Normal equations

x_1	y_1	x_2	y_2	. . .	x_u	y_u	C_1	C_2	. . .	C_k	η
[aa]	[ab]	[ac]	[ad]	. . .	[as]	[at]	[aℓ]	[am]	. . .	[ak]	[aN]
[ab]	[bb]	[bc]	[bd]	. . .	[bs]	[bt]	[bℓ]	[bm]	. . .	[bk]	[bN]
[ac]	[bc]	[cc]	[cd]	. . .	[cs]	[ct]	[cℓ]	[cm]	. . .	[ck]	[cN]
[ad]	[bd]	[cd]	[dd]	. . .	[ds]	[dt]	[dℓ]	[dm]	. . .	[dk]	[dN]
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
[as]	[bs]	[cs]	[ds]	. . .	[ss]	[st]	[sℓ]	[sm]	. . .	[sk]	[sN]
[at]	[bt]	[ct]	[dt]	. . .	[st]	[tt]	[tℓ]	[tm]	. . .	[tk]	[tN]
[aℓ]	[bℓ]	[cℓ]	[dℓ]	. . .	[sℓ]	[tℓ]	0	0	. . .	0	[ℓN] + η_1
[am]	[bm]	[cm]	[dm]	. . .	[sm]	[tm]	0	0	. . .	0	[mN] + η_2
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . . . .
[ak]	[bk]	[ck]	[dk]	. . .	[sk]	[tk]	0	0	. . .	0	[kN] + η_k

Illustrative problem--Given a simple triangulation base net as shown in Figure 1, consider a specific solution of an adjustment. In this net there are two stations, 1 and 5, fixed in position, length, and azimuth; three new stations, 2, 3, and 4; and a measured base line between 2 and 4 to be held fixed. The adjustment thus involves three pairs of unknowns representing corrections to the latitude and longitude of the new stations, a set of five "z" conditions to insure that after adjustment the sum of the residuals around each station will be zero, and one length condition in order to hold the base fixed in length.

Table 3 shows the numerical values of the observation and condition equations which are required for the adjustment of the net. Following the procedure outlined in the general problem, the normal equations are formed from Table 3 and are shown in Table 4, along with the solution of these normal equations. The coefficients of the length condition are shown in the C_1 column of Table 3. The η_1 term of this equation is +2.48. The [ℓN] + η_1 term appearing in the η column for

Table 3--Matrix for formation of normal equations

Direction	z_1	z_2	x_2	y_2	z_3	x_3	y_3	z_4	x_4	y_4	z_5	C_1	N	Σ-	V's	Adopted residuals
1	+1		+ 9.12	+16.93								+0.58	0	+27.63	-0.8744	-0.87
2	+1					+10.37	+ 9.20						+1.03	+21.60	+0.1097	+0.11
3	+1											-0.58	+1.64	+ 2.06	+0.4817	+0.48
4	+1								+35.97	-12.84			-1.02	+23.11	+0.2829	+0.28
5		+1	-33.91	- 2.38		+33.91	+ 2.35						0	+ 0.97	+0.3386	+0.34
6		+1	- 7.75	+ 9.31					0			-0.85	+0.45	+ 2.16	-0.6395	-0.64
7		+1	0	+18.32						-18.32			+0.32	+ 1.32	-0.2039	-0.21
8		+1	+ 9.12	+16.92								+0.85	+2.00	+29.89	+0.5047	+0.51
9					+1	- 4.84	+13.54						0	+ 9.70	+0.2826	+0.28
10					+1	+ 7.21	+13.92		- 7.22	-13.92			-0.81	+ 0.18	-0.2566	-0.26
11					+1	+10.37	+ 9.18						-0.19	+20.36	+0.4522	+0.45
12			-33.91	- 2.38	+1	+33.91	+ 2.35						-3.00	- 2.03	-0.4784	-0.48
13								+1	+35.97	-12.87			0	+24.10	-0.6121	-0.61
14			0	+18.32				+1	0	-18.32		+0.35	+2.35	+ 3.70	+0.5307	+0.53
15						+ 7.21	+13.93	+1	- 7.22	-13.93			+2.95	+ 3.94	+0.0253	+0.03
16								+1	-18.45	+ 3.07		-0.35	+4.29	-10.44	+0.0561	+0.06
17									-18.45	+ 3.10	+1	+2.44	+0.33	-11.58	-0.5300	-0.53
18											+1		0	+ 1.00	+0.3005	+0.30
19			- 7.75	+ 9.33							+1	-2.44	-0.36	- 0.22	+0.6306	+0.63
20						- 4.84	+13.55				+1		-0.58	+ 9.13	-0.4011	-0.40

Table 4--Solution of 12 normal equations

	s_1	s_2	x_2	y_2	s_3	x_3	y_3	s_4	x_4	y_4	s_5	c_1	w	Σ
	+ 4		+ 9.12	+ 16.93		+ 10.37	+ 9.20		+ 35.97	- 12.84		0	+ 1.65	+ 74.40
(-1.15827)	s_1		- 2.28000	- 4.23250		- 2.59250	- 2.30		- 8.99250	+ 3.21			- 0.41250	- 18.60000
	+ 4		- 32.54	+ 42.17		+ 33.91	+ 2.35			- 18.32		0	+ 2.77	+ 34.34
(-1.77880)		s_2	+ 8.13500	- 10.54250		- 8.47750	- 0.58750			+ 4.58000			- 0.69250	- 8.58500
			+2586.2500	+ 325.6636	- 33.91	-2299.7762	- 159.3770				- 7.75	+ 38.5391	+ 119.2725	+ 545.4920
			+2300.7435	+ 630.1162	- 33.91	-2047.5620	- 161.2358		- 82.0116	- 119.7580	- 7.75	+ 38.5391	+ 138.0444	+ 655.2158
	(-0.04177)	x_2	- 0.27388	+ 0.01474	+ 0.88996	+ 0.07008			+ 0.03565	+ 0.05205	+ 0.00337	- 0.01675	- 0.06000	- 0.28478
			+1429.2099	- 2.38	- 161.4116	- 11.1860	+ 18.32			- 671.2448	+ 9.33	- 0.0653	+ 90.7251	+1086.0609
			+ 740.4002	+ 6.9079	- 2.0206	- 30.7413	+ 18.32		- 129.7794	- 390.9634	+ 11.4535	- 10.6197	+ 16.7318	+ 229.6890
	(+0.03927)	y_2	- 0.00933	+ 0.00273	+ 0.04152	- 0.02474			+ 0.17528	+ 0.52804	- 0.01547	+ 0.01414	- 0.00260	- 0.31023
				+ 4	+ 46.65	+ 38.99			- 7.22	- 13.92			- 4.00	+ 28.21
				+ 3.4357	+ 16.4903	+ 36.9004	- 0.1709	-	7.2181	- 12.0374	- 0.2212	+ 0.6671	- 2.1215	+ 35.7244
	(+0.40421)	s_3			- 4.79969	- 10.74029	+ 0.04974	+	2.10091	+ 3.50362	+ 0.06438	- 0.19417	+ 0.61749	- 10.39801
					+2665.4694	+ 419.6605	+ 7.21	-	104.1124	- 200.7985	- 4.84		- 74.7826	+ 337.7486
					+ 449.9110	+ 55.1997	+ 8.0802	-	236.0697	- 62.0698	- 10.6474	+ 31.0658	+ 30.5391	+ 266.0089
				(+0.02347)	x_3	- 0.12269	- 0.01796	+	0.52470	+ 0.13796	+ 0.02167	- 0.06905	- 0.06788	- 0.59125
						+ 934.7028	+ 13.93	-	201.0770	- 387.8113	+ 13.55		+ 22.6411	+ 695.5731
						+ 496.4929	+ 15.5346	-	188.4567	- 235.2409	+ 17.1644	- 8.7166	+ 46.6263	+ 143.4040
					(-0.00059)	y_3	- 0.03129	+	0.37958	+ 0.47381	- 0.03457	+ 0.01756	- 0.09193	- 0.28982
							+ 4	+	10.30	- 42.05		0	+ 9.59	+ 21.30
							+ 2.9071	+	23.2884	- 24.4999	- 0.6402	+ 0.0107	+ 7.0631	+ 8.1292
						(-3.07418)	s_4	-	8.01087	+ 8.42761	+ 0.22022	- 0.00368	- 2.42960	- 2.79632
									+1372.7436	- 837.5482	- 18.45	- 38.5695	- 137.3792	+2074.6663
									+2626.4868	- 745.7667	- 11.1276	- 24.7407	- 171.6793	+1673.1725
								(+0.05799)	x_4	+ 0.28394	+ 0.00424	+ 0.00942	+ 0.06516	- 0.61704
										+1408.5935	+ 3.10	+ 0.0775	- 51.4426	- 824.2044
										+ 490.3681	+ 6.0753	- 7.9655	+ 12.2152	+ 500.6931
									(-0.02923)	y_4	- 0.01239	+ 0.01624	- 0.02491	- 1.02106
											+ 4	0	- 0.61	- 1.67
											+ 2.6736	+ 1.3698	- 0.7528	+ 3.2906
										(+0.30051)	s_5	- 0.51234	+ 0.28157	- 1.23077
												0	+ 3.8509	+ 3.8417
											- 4.2898	- 0.1586	- 4.4484	
											(-0.03697)	c_1	- 0.03697	- 1.03697

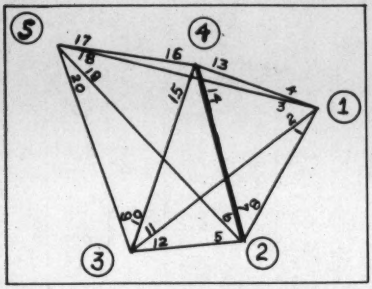

Fig. 1--Sketch of a simple triangulation base net

the last normal equation in Table 4 is computed as follows: (+0.58) (0) + (−0.58) (+1.64) + (−0.85) (+0.45) + (+0.85) (+2.00) + (+0.35) (+2.35) + (−0.35) (+4.29) + (+2.44) (+0.33) + (−2.44) (−0.36) + 2.48 = +3.8509.

The unknowns computed in the back solution are shown in Table 4 in parentheses along the diagonal elements. Substitution of these unknowns in the original observation equations yields the v's shown to the right of Table 3.

The entire Doolittle solution is accomplished by means of a modern calculating machine and hence accumulations of squares and cross products are carried in the machine with the results indicated in Table 4, that is, sums of squares and cross products equivalent to [bb 1], [cc 2], [dd 3] . . ., [bd 1], [cd 2], and so forth. The residuals given in Table 3 satisfy the length condition rigorously, and satisfy the condition that at each station their sum be zero.

The small shifts in latitude and longitude represented by the unknowns (x's and y's) of the back solution will satisfy the requirement that the interior angles of each triangle in Figure 1 will add to 180° plus spherical excess and the length of a given side calculated from any one triangle will agree with the length of that side calculated from any other triangle.

Inasmuch as the illustrative problem involves a small number of normal equations, the divisions by the leading diagonal elements are shown only to five decimal places in Table 4. In general, these divisions should be carried out to six decimals and in some cases to seven decimals in order to maintain sufficient significant figures.

The adjustment problem in this paper was selected for its simplicity and would not ordinarily be carried out by the method of variation of geographic coordinates. The method of condition equations would be employed. The method of variation of coordinates is most practical where the scheme of triangulation to be adjusted is in the form of a large area with many lines radiating from each station.

The geodetic literature apparently does not include the problem of least-squares adjustment of a system of observation equations subject to rigorous conditions for Laplace azimuth and base-line measurements. JORDAN [1885] does go into the problem of fictitious observation equations for the "z" conditions as does HELMERT [1880].

The writers feel that the method outlined in this paper is all inclusive in scope, flexible in technique, and results in a simplified and straightforward solution.

Acknowledgment--The writers desire to make acknowledgment to L. E. Shmidl, Senior Mathematician, for his helpful advice and for his suggestion for the investigation of possible application of the procedure to the field of education and other fields in addition to that of engineering.

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A THEORY OF MICROSEISMS WITH GEOLOGIC APPLICATIONS

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Abstract--A theory for the origin of microseisms based on the normal mode propagation of sound in two layers is given. It explains the mechanism of transmission of seismic energy from a storm at sea and predicts that periods of three to nine sec will predominate, depending on the depth of the water and the elastic properties of the bottom.

It is shown that this theory can be used to infer elastic properties of the ocean bottom, to a depth of the order of several times the depth of the water, by a study of the periods of microseisms originating from storms whose positions are known.

Basic data about microseisms

Microseisms are minute oscillations of the ground which are recorded at times on all of the sensitive seismographs of the world, and on occasions cause serious interference with delicate physical measurements. Their periods range from three to ten sec, their amplitudes up to about 30μ. They occur in microseismic storms, which is a term applied to a period of a few days during which the microseisms are continuously above average intensity. They are more prominent in winter than in summer. The mean intensity at all stations in an area of continental dimensions goes up and down together, and it is now generally agreed that microseisms originate at a storm (marked barometric depression) over the ocean. It has long been conceded by all students of the subject that microseisms were intimately connected with storms at sea, but there has been divergence of opinion about the mechanism by which the storm communicates energy to the solid Earth more effectively over the oceans than over the continents.

Introduction

The present theory originated in experiments on the transmission of explosive sounds in water ten to 20 fathoms deep, where dispersion effects were discovered which showed that the group velocity had a minimum value in the neighborhood of 20 to 60 cycles per sec, depending upon the depth of the water and the properties of the bottom. At extreme ranges the predominant signal consisted of a train of five or ten waves whose frequency was very close to that corresponding to the minimum value of group velocity. Preliminary calculations about a proposed similar experiment in oceanic depths predicted that the periods would lie in the range of periods observed for microseisms. The theory of propagation of sound through a system consisting of the water and the elastic bottom showed that the sea surface is an antinode for vertical motion, hence the proper place for application of forces to produce vibrations in the system. The role of the sea water in the origin of microseisms and the periods observed for microseisms are thus explained by a single theory. Through application of this theory to microseism data, important facts about the structure of the ocean bottom can be inferred.

Sound propagation in the ocean

Liquid bottom theory--The complete theory for the normal mode propagation of sound in two liquid layers was given by PEKERIS [see "References" at end of paper, 1948], who had solved the problem for waves originating at an impulsive point source. (Pekeris worked on aspects of this problem at various times during 1941 to 1944. He issued a detailed exposition of the theory with application to observational data in a N. D. R. C. report in January 1945, which forms the basis of his 1948 publication.) Pekeris showed conclusively that his solution fully explained most of the characteristics of explosive sounds in shallow water observed by EWING and WORZEL [1948]. The reader is referred to the Pekeris paper for a complete exposition of the theory and its experimental verification. For the purposes of the present paper, it will be sufficient to present an abbreviated derivation of that portion of the theory pertinent to the problem of microseisms.

Let us consider the propagation of plane sound waves through a liquid layer of thickness H, density ρ_1, sound velocity V_1, superposed upon an infinitely thick liquid layer of density ρ_2 and

sound velocity V_2. The cartesian coordinate system is taken with the x-axis in the free surface parallel to the direction of propagation, and the y-axis vertically downward. We introduce the velocity potential $\phi(x, y, t)$, related to the acoustic pressure p and the horizontal and vertical particle velocity components $\dot{u}$ and $\dot{v}$ by the equations

$$\left.\begin{aligned} \partial\phi/\partial x &= \dot{u} \\ \partial\phi/\partial y &= \dot{v} \\ \rho\,\partial\phi/\partial t &= p \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

It is required to find functions ϕ_1 and ϕ_2 which satisfy the wave equations

$$\partial^2\phi_1/\partial t^2 = V_1^2\nabla^2\phi_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in the water (upper layer),

$$\partial^2\phi_2/\partial t^2 = V_2^2\nabla^2\phi_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in the bottom, subject to the boundary conditions

$$\left.\begin{aligned} p &= 0 && \text{at } y = 0 \\ \rho_1\partial\phi_1/\partial t &= \rho_2\partial\phi_2/\partial t && \text{at } y = H \\ \partial\phi_1/\partial y &= \partial\phi_2/\partial y && \text{at } y = H \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

It can readily be verified that solutions are of the form

$$\phi_1 = A \sin(\xi y) \exp[i(kx - \omega t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$\phi_2 = B \exp(-\eta y) \exp[i(kx - \omega t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where the period T and the wavelength L are given by $\omega = 2\pi/T$ and $k = 2\pi/L$. The separation constants ξ and η are obtained by substituting (5) and (6) in (2) and (3), with the result

$$\left.\begin{aligned} \xi^2 &= \omega^2/V_1^2 - k^2 \\ \eta^2 &= k^2 - \omega^2/V_2^2 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The factor $\exp[i(kx - \omega t)]$ must be the same for (5) and (6) in order for the boundary conditions to hold independent of x and t. The function ϕ_2 is chosen to decrease exponentially with depth, since we are interested in solutions for which the loss of energy by refraction into the bottom is zero. If we introduce the phase velocity $C = \omega/k$, (7) may be rewritten in the form

$$\left.\begin{aligned} \xi^2 &= k^2(C^2/V_1^2 - 1) \\ \eta^2 &= k^2(1 - C^2/V_2^2) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Substituting (5) and (6) in (4), and eliminating A and B between the resulting expressions gives the period equation

$$\tan[kH(C^2/V_1^2 - 1)^{1/2}] = -(\rho_2/\rho_1)(C^2/V_1^2 - 1)^{1/2}(1 - C^2/V_2^2)^{-1/2} \quad \ldots\ldots (9)$$

Equation (9) gives the period $T = 2\pi/Ck$ as a function of phase velocity C. Numerical calculation shows the period to be a multiple valued function of phase velocity, each value belonging to a distinct mode. For the case $V_2 \geq C \geq V_1$, C and k are real and the wave propagation defined by the solutions (5) and (6) will be undamped.

A consequence of the dispersion indicated by the dependence of phase velocity on period given by (9) is that the energy associated with each wave length (or period) is propagated with the group velocity U given by the well known formula

$$U = C + kdC/dk \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Carrying out the indicated differentiation we obtain

$$U = C - V_1 kH(C^2/V_1^2 - 1)/\left\{kHC/V_1 + (\rho_2/\rho_1)(C/V_1)(1 - V_1^2/V_2^2) \times (1 - C^2/V_2^2)^{-3/2} \cos^2[kH(C^2/V_1^2 - 1)^{1/2}]\right\} \quad \ldots\ldots\ldots\ldots (11)$$

The graphs of U/V_1 and C/V_1 are plotted as functions of $\gamma = kHC/2\pi V_1 = H/V_1 T$ in Figure 1 for $\rho_2 = 2\rho_1$, and various values of the ratio V_2/V_1 as indicated. These curves are taken directly from the report of Pekeris.

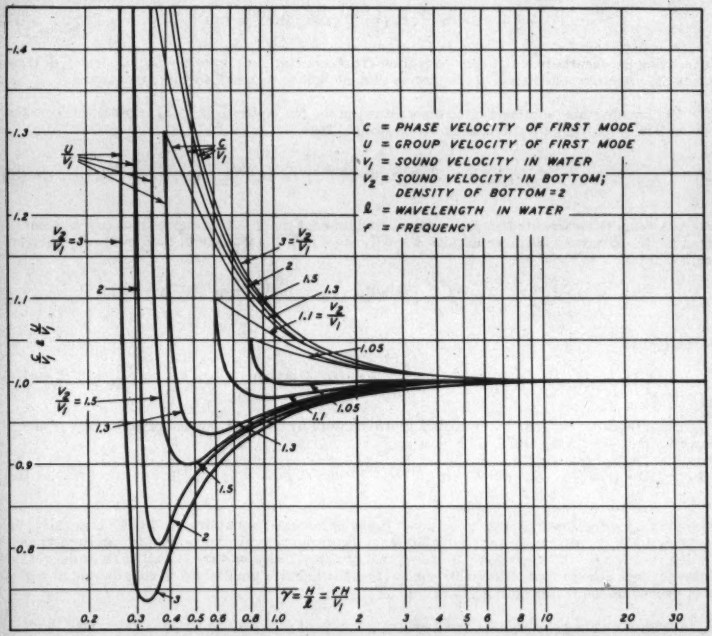

Fig. 1--Phase and group velocity curves for normal mode propagation in two liquid layers (after Pekeris)

In (5), ϕ_1 for any given mode represents a wave in the first layer progressing in the x direction and having a vertical standing sinusoidal wave pattern. From (1) and (5) the components of particle motion in the first layer are for the nth mode

$$\dot{u}_1^{(n)} = A^{(n)} ik^{(n)} \sin(\xi_\zeta^{(n)} y) \exp[i(k^{(n)} x - \omega t)] \quad \ldots\ldots\ldots\ldots (12)$$

$$\dot{v}_1^{(n)} = A^{(n)} \xi_\zeta^{(n)} \cos(\xi_\zeta^{(n)} y) \exp[i(k^{(n)} x - \omega t)] \quad \ldots\ldots\ldots\ldots (13)$$

These equations show that the motion of a surface particle y = 0 for all modes is vertical and that the surface is always an antinode for vertical motion. Equation (13) shows that there also will be antinodes of vertical motion at the depths $y = m\pi/\xi^{(n)} \leq H$, where m is an integer and $\xi^{(n)}$ depends on period and mode through (9). It can be shown that for the nth mode there are (n - 1) antinodal planes for vertical motion in the liquid layer beneath the free surface. It follows from (12) and (13) that antinodes for vertical motion correspond to modes of pressure and horizontal motion.

In a similar manner the motion in the bottom can be derived from (6). Here ϕ_2 is a wave traveling within the bottom in the x direction with the particle velocities

$$\dot{u}_2^{(n)} = B^{(n)} ik^{(n)} \exp(-\eta^{(n)} y) \exp[i(k^{(n)} x - \omega t)] \quad \ldots\ldots\ldots\ldots\ldots (14)$$

$$\dot{v}_2^{(n)} = -B^{(n)} \eta^{(n)} \exp(-\eta^{(n)} y) \exp[i(k^{(n)} x - \omega t)] \quad \ldots\ldots\ldots\ldots\ldots (15)$$

decreasing exponentially with depth. Equation (7) shows that η is large for short periods (k large), hence the effective penetration of the motion into the bottom is small for high frequencies.

The steady state solution for the disturbance in the top layer $\Phi_0(x, y, t)$ is obtained from the summation of the velocity potentials of each mode. Thus

$$\Phi_0(x, y, t) = \sum_{n=1}^{\infty} A^{(n)} \sin(\xi^{(n)} y) \exp[i(k^{(n)} x - \omega t)] \quad \ldots\ldots\ldots\ldots (16)$$

where $A^{(n)}(\omega)$ is an amplitude factor associated with each mode. This expression can be generalized for the arbitrary initial conditions $\dot{v} = \partial\Phi/\partial y = f(x)$, $\Phi = 0$ at $y = 0$, $t = 0$ by the Fourier integral

$$\Phi(x, y, t) = (1/2\pi) \sum_{n=1}^{\infty} \int_{-\infty}^{\infty} g(k^{(n)}) [\sin(\xi^{(n)} y)/\xi^{(n)}] \exp[i(k^{(n)} x - \omega t)] dk^{(n)} \quad \ldots (17)$$

where g(k) is

$$g(k) = \int_{-\infty}^{\infty} f(x) \exp(-ikx) dx \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

The integral of (17) can be evaluated approximately by Kelvin's method of stationary phase [for example, see LAMB, 1932, p. 395], giving

$$\Phi(x, y, t) = (1/\sqrt{2\pi}) \sum_{n=1}^{\infty} [g(k^{(n)}) \sin(\xi^{(n)} y)/\xi^{(n)} \sqrt{(x/U) \left| dU/dk \right|}] \exp[i(k^{(n)} x - \omega t \pm \pi/4)]. \quad (19)$$

where the upper or lower sign is to be taken in the exponential according as dU/dk is negative or positive, and k, U, dU/dk, ξ, are evaluated from the group velocity curve for the values of x, and t which satisfy x/t = U. Equation (19) shows that the amplitudes of waves of all periods decrease as the inverse square root of the distance and that the relative amplitudes of each period at a given point depend on the factor $g(k)/\xi \sqrt{(x/U) \left| dU/dk \right|}$.

A typical sequence of signals received from a distant explosion in shallow water may be described by referring to any one of the group-velocity curves of Figure 1. The first arrivals, corresponding to the extreme left end of the group velocity curves, are low frequency waves which have traveled through the ground with the velocity of sound in the bottom. These are followed by waves of slowly increasing frequency. At the time corresponding to travel with normal speed in water, high frequency waves arrive superposed on the earlier low frequency waves. These high frequency waves correspond to the extreme right hand end of the group velocity curve. Their frequency rapidly decreases until a time corresponding to travel at the group velocity minimum, at which the frequency is the same as that approached by the left branch. Pekeris has named this part of the signal the Airy phase, and the frequency arriving then the Airy frequency.

A seismogram illustrating this sequence of arrivals from a shot of 1/2 lb in water 65 feet deep at a distance of 2.5 nautical miles is shown in Figure 2. As JEFFREYS [1925] mentioned in pointing out the application of classical results on dispersion and group velocity to earthquake waves, the energy in a given frequency band will continually spread over a wider belt due to the

differing rates of propagation of energy, except for frequencies in the vicinity of a stationary value of group velocity such as the minimum shown in Figure 1.

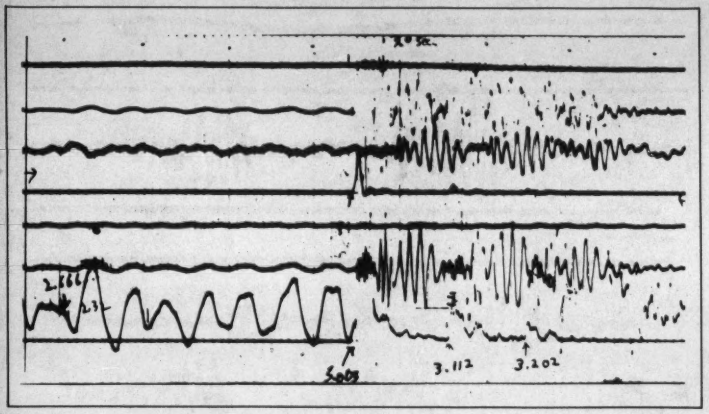

Fig. 2--Typical seismogram illustrating the sequence of arrivals from a shallow water shot

That large amplitudes are associated with stationary values of group velocity can be seen from (19), where the term dU/dk occurs in the denominator. The integral breaks down and requires a finer degree of approximation for the case dU/dk = 0, as shown, for example, by JEFFREYS [1925] or PEKERIS [1948]. We therefore expect that the Airy frequency would become predominant at great ranges. Figure 3, the seismogram from a shot of five lb in water 57 feet deep, at a distance of 4.5 nautical miles illustrates the predominance of the Airy phase.

Solid bottom theory--Although this treatment of the bottom as a liquid was adequate for the shallow water data to which Pekeris applied it, when dealing with the ocean basins it is necessary to consider also the case where the bottom is an elastic solid.

STONELEY [1926] gave a theory for the effect of the ocean on the propagation of Rayleigh Waves along the bottom. He obtained a period equation and calculated values of phase and group velocity for an ocean with a granitic bottom, but the lowest period for which his calculations were carried out was 20 sec for a six km ocean. He did not discover a minimum value of group velocity, primarily because it occurs at shorter periods than those which occur in the Rayleigh Waves in which he was interested. Stoneley's emphasis was on the propagation of energy as Rayleigh waves in the bottom. In the work which led up to the present paper [EWING and WORZEL, 1947], the emphasis was originally on the energy flux through the water. It is now obvious, and will be shown, that we are dealing with the propagation of energy in a single acoustic system consisting of both water and bottom.

Let us consider the propagation of plane elastic waves through a liquid layer of thickness H, density ρ_1, and compressional wave velocity V_1, superposed upon an infinitely thick, rigid bottom of density ρ_2 whose compressional and distortional wave velocities are respectively α_2 and β_2. λ_1 is the compressibility of the liquid, λ_2, μ_2 are Lame's constants for the bottom and are related to the elastic wave velocities as follows

$$\left.\begin{aligned} V_1^2 &= \lambda_1/\rho_1 \\ \alpha_2^2 &= (\lambda_2 + 2\mu_2)/\rho_2 \\ \beta_2^2 &= \mu_2/\rho_2 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

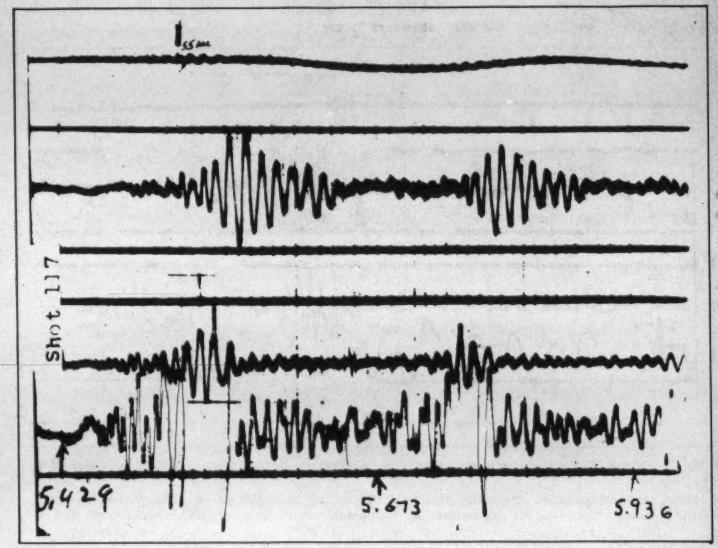

Fig. 3--Seismogram from a shallow water shot illustrating the predominance at large distances of periods corresponding to minimum values of group velocity; the secondary arrival at about 5.7 seconds is due to the oscillation of the gas bubble

The cartesian coordinate system is chosen as before, and the subscripts 1 and 2 refer to the liquid layer and bottom, respectively.

We introduce the functions $\phi(x, y, t)$ and $\psi(x, y, t)$ defined by the equations

$$\left.\begin{aligned} u_1 &= \partial\phi_1/\partial x \\ v_1 &= \partial\phi_1/\partial y \\ u_2 &= \partial\phi_2/\partial x + \partial\psi_2/\partial y \\ v_2 &= \partial\phi_2/\partial y - \partial\psi_2/\partial x \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (21)$$

where u and v are the horizontal and vertical particle displacements. The procedure is that of LAMB [1917]. The vertical stress p_{yy} and the tangential stress p_{xy} can be expressed in terms of ϕ, ψ, and the elastic constants as follows

$$p_{yy} = \lambda\nabla^2\phi + 2\mu(\partial^2\phi/\partial y^2 - \partial^2\psi/\partial x\partial y) \quad \ldots\ldots\ldots\ldots\ldots (22)$$

$$p_{xy} = \mu(\partial^2\psi/\partial y^2 - \partial^2\psi/\partial x^2 + 2\partial^2\phi/\partial x\partial y) \quad \ldots\ldots\ldots\ldots\ldots (23)$$

It is required that the functions ϕ and ψ satisfy the wave equations

$$\partial^2\phi_1/\partial t^2 = V_1^2\nabla^2\phi_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots (24)$$

in the liquid,

$$\partial^2\phi_2/\partial t^2 = \alpha_2^2\nabla^2\phi_2 \quad \ldots\ldots (25)$$

$$\partial^2\psi_2^2/\partial t^2 = \beta_2^2\nabla^2\psi_2 \quad \ldots\ldots (26)$$

in the bottom, and the boundary conditions

$$(p_{yy})_1 = 0 \qquad \text{at } y = 0 \quad \ldots\ldots (27)$$

$$(p_{yy})_1 = (p_{yy})_2 \qquad \text{at } y = H \quad \ldots\ldots (28)$$

$$(p_{xy})_2 = 0 \qquad \text{at } y = H \quad \ldots\ldots (29)$$

$$v_1 = v_2 \qquad \text{at } y = H \quad \ldots\ldots (30)$$

The gravity term has been omitted, Stoneley having shown it to be of negligible effect for periods under 20 sec.

It can readily be verified that solutions of (24), (25), and (26) are of the form

$$\phi_1 = A \sin(\xi y) \exp[i(kx - \omega t)] \quad \ldots\ldots (31)$$

$$\phi_2 = B \exp(-\eta y) \exp[i(kx - \omega t)] \quad \ldots\ldots (32)$$

$$\psi_2 = C \exp(-\zeta y) \exp[i(kx - \omega t)] \quad \ldots\ldots (33)$$

where

$$\xi^2 = \omega^2/V_1^2 - k^2 = k^2(C^2/V_1^2 - 1) \quad \ldots\ldots (34)$$

$$\eta^2 = k^2 - \omega^2/\alpha_2^2 = k^2(1 - C^2/\alpha_2^2) \quad \ldots\ldots (35)$$

$$\zeta^2 = k^2 - \omega^2/\beta_2^2 = k^2(1 - C^2/\beta_2^2) \quad \ldots\ldots (36)$$

and k is the wave number related to the wavelength L (measured in the direction of x) by $k = 2\pi/L$. ϕ_2 and ψ_2 are taken to decrease exponentially with depth since we are interested in the case where no energy is lost by refraction into the bottom. The factor $(kx - \omega t)$ is the same for all ϕ and ψ in order for the boundary conditions (27) to (30) to hold independent of x and t.

In (31), (32), and (33), ϕ_1, ϕ_2, and ψ_2 make up a wave system progressing in the x direction with a phase velocity $C = \omega/k$ and having a vertical standing sinusoidal wave pattern in the liquid layer. ϕ_1 and ϕ_2 represent compressional waves and ψ_2 represents distortional waves polarized vertically. The particle displacements and the location of antinodal planes in the liquid layer can be discussed in a manner similar to the method used for the two liquid layer theory. It will be shown later that the wave system consists of Rayleigh-type waves at the bottom interface and multiply-reflected compressional waves undergoing constructive interference in the liquid layer.

The first boundary condition, (27), has been satisfied by the choice of ϕ_1. If (31)to (33) are substituted in the boundary conditions (27) to (30), three independent homogeneous equations in the unknowns A, B, and C, are obtained. Any two of the three unknowns can be found in terms of the third. For a solution for A, B, and C to exist, however, the determinant of their coefficients must vanish as follows

$$\begin{vmatrix} -(\xi^2 + k^2)\sin(\xi H) & -[(\lambda_2/\lambda_1)(\eta^2 - k^2) + 2(\mu_2/\lambda_1)\eta^2]\exp(-\eta H) & -2i(\mu_2/\lambda_1)\zeta k \exp(-\zeta H) \\ 0 & -2i\mu_2\eta k \exp(-\eta H) & \mu 2(\zeta^2 + k^2)\exp(-\zeta H) \\ \xi\cos(\xi H) & \eta \exp(-\eta H) & ik \exp(-\zeta H) \end{vmatrix} = 0 \quad \ldots\ldots (37)$$

The common factor $i(kx - \omega t)$ has been cancelled from each term. Substituting for ξ, η, ζ, and λ_1, λ_2, μ_2 from (34), (35), (36), and (20), respectively, and using Poisson's assumtion $\lambda_2 = \mu_2$, the determinant reduces to the period equation

$$\tan\left[kH(C^2/V_1^2 - 1)^{1/2}\right] = (\rho_2/\rho_1)(\beta_2^4/C^4)(C^2/V_1^2 - 1)^{1/2}(1 - C^2/\alpha_2^2)^{-1/2} \times$$

$$[4(1 - C^2/\alpha_2^2)^{1/2}(1 - C^2/\beta_2^2)^{1/2} - (2 - C^2/\beta_2^2)^2] \quad \ldots\ldots\ldots\ldots\ldots (38)$$

Equation (38) defines an implicit relation between the period $T = 2\pi/Ck$ and the phase velocity C with the elastic properties of the system as parameters. Those values of k real for a given real value of C correspond to undamped propagation. It can be seen from (31), (32), and (33) that if k has an imaginary component for a given value of C the wave system is propagated with damping, the degree of attenuation depending on the magnitude of the imaginary component. The energy loss associated with damped propagation is due to refraction into the bottom. For the case $\alpha_2, \beta_2 > V_1$, which is considered in this paper, undamped propagation will occur for $\alpha_2 > \beta_2 \geq C \geq V_1$.

For Hk small, or $H << L$, $\tan\left[kH(C^2/V_1^2 - 1)^{1/2}\right] \approx 0$ and the period equation reduces to the algebraic equation for the velocity of Rayleigh waves propagated along the surface of a semi-infinite solid. This simply means that for wave lengths large compared to the depth of the liquid layer, the effect of the liquid layer can be neglected and the propagation reduces to Rayleigh waves on the surface of the solid bottom.

The solutions ϕ_1, ϕ_2, and ψ_2 can be generalized for an initial arbitrary disturbance and the result summed up for all modes as was done earlier for the two liquid theory.

It is convenient and instructive at this point to derive the period equation geometrically, for this method offers a clear physical picture of normal mode propagation and the origin of the period equation.

A constant frequency line source acting on the surface of the liquid layer produces compressional waves which in general will be propagated, away from the source along ray paths undergoing multiple reflections from the free surface and the bottom interface. The ray paths may be defined by the angle of incidence θ where $0 \leq \theta \leq \pi/2$. At distances which are large compared to the wavelength, the waves may be treated as plane.

Undamped propagation will occur only for those rays for which no energy is refracted into the bottom, that is, those rays undergoing total reflection at the bottom. Waves reflected from the free surface will undergo a phase change of $-\pi$. Total reflection from the bottom interface produces a phase change of $-\epsilon$ where ϵ is given by JEFFREYS [1926].

$$\operatorname{ctn}(\epsilon/2) = (\rho_2/\rho_1)(\beta_2^4/C^4)(C^2/V_1^2 - 1)^{1/2}(1 - C^2/\alpha_2^2)^{-1/2} \times$$

$$[(2 - C^2/\beta_2^2)^2 - 4(1 - C^2/\alpha_2^2)^{1/2}(1 - C^2/\beta_2^2)^{1/2}] \quad \ldots\ldots\ldots\ldots\ldots (39)$$

and

$$C = V_1/\sin\theta$$

The disturbance at a distant point will be a maximum for those ray paths for which constructive interference occurs between the multiply-reflected rays. The period equation is simply the mathematical statement of this condition.

In Figure 4 ADEF represents a portion of a ray path of a plane wave which has been totally reflected at the bottom with a phase change $-\epsilon(\theta)$ and reflected at the free surface with a phase change of $-\pi$. As the wave front (shown by the dashed line) moves a distance $BC = V_1$ in unit time, a point on the wave front moves a distance GH in the horizontal direction, where $GH = C = V_1/\sin\theta$ and C is the phase velocity defined earlier. For this representation the wave number k may be defined by the equation $k = (2\pi/\ell)\sin\theta$ where ℓ is the wave length in the water as measured along a ray path. If the wave front at E is to interfere constructively with the coincident wave front which has traversed the additional path BDE, it is required that $(2\pi/\ell)BDE - \epsilon(\theta) - \pi = 2(n-1)\pi$ where $n = 1, 2, 3, \ldots$ From the geometry of Figure 4 $BDE = 2H\cos\theta$ and the previous equation can be rewritten as

$$(2\pi/\ell)\, H\cos\theta = \epsilon/2 + (2n - 1)\pi/2 \quad \ldots\ldots\ldots\ldots\ldots (40)$$

The integers n determine the normal modes of propagation. For each value of n there is a fixed relationship between ℓ and θ (or C) for which constructive interference occurs. This is the dependence of wave length on phase velocity expressed by the period equation. Taking the tangent of both sides of (40) and using the above definitions of ϵ, k, and C, we can rewrite it in the form derived earlier, (38). It is apparent that the period equation for the liquid bottom theory could have been derived geometrically in a similar manner.

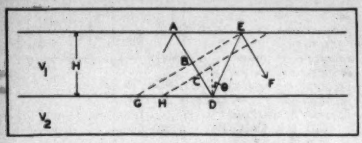

Fig. 4--Ray diagram for propagation of elastic waves in two layers

From these considerations it can be seen that for plane waves of a given frequency the disturbance at a distant point of the first layer is obtained by the superposition of waves arriving at the point along oblique ray paths. In the process of superposition, the combination of upgoing and downgoing waves results in a single disturbance traveling in the x direction and having a standing sinusoidal wave pattern from the surface to the bottom, (5) or (31), as the case may be. It is found that for certain angles of incidence there is constructive interference between the multiply reflected waves of a given period. The period equation, (9) or (38) gives the exact relationship between the frequency and angle of incidence for which constructive interference occurs. The velocity potential of a given mode at the point is made up of waves whose periods and paths satisfy the period equation. This is the basis of the normal mode solutions. The continuous distribution of values of T and θ (or C) obtained from (40) for a given n determine the nth mode. The summation of the velocity potentials for all modes n = 1 to ∞ gives the resultant disturbance.

The motion in the bottom consists of a wave disturbance progressing parallel to the boundary with an amplitude which decreases exponentially with depth from the interface (see Eq. (32) and (33). These boundary waves may be thought of as originating in the process of total reflection of compressional waves obliquely incident on the interface in a manner similar to the boundary waves associated with the total reflection of light. They can also be considered as Rayleigh waves modified by the presence of the liquid layer. Both points of view are essentially the same since they ultimately go back to solutions of a wave equation which satisfy a common set of boundary conditions.

The period equation (38) was used to obtain the phase velocity as a function of period. The group velocity was subsequently determined by numerical differentiation. The results of these computations are shown in Figure 5, where C/V_1 and U/V_1 are plotted as functions of the dimensionless parameter $\gamma = H/\ell = H/V_1T = HkC/2\pi V_1$ for the case $\rho_2/\rho_1 = 2.5$, $\alpha = \sqrt{3}\beta$, $\beta = 2V_1$. The numerical computations show the period equation to consist of two distinct branches. The phase and group velocity of the first branch approach the velocity of true Rayleigh waves in the bottom layer as γ becomes very small, or as the wavelength becomes large with respect to the thickness of the first layer. As $C/V_1 \to 1$, γ approaches a limiting value corresponding to a cutoff period. The first branch is further characterized by the existence of a minimum value of group velocity. From the values of ξ and k obtained for the first branch in the numerical computation it can be shown that (1) there are no antinodes in the liquid layer beneath the free surface (2) there are no higher modes. Stoneley's calculations of phase and group velocity were limited to the first branch and did not extend to periods small enough to include the minimum value of group velocity. Jeffreys, in a note at the end of Stoneley's paper, predicted the existence of a minimum value of group velocity at periods too short to be of interest in the study of earthquake waves.

In the second branch the phase velocity equals the velocity of shear waves in the bottom ($C = \beta = 2V_1$) for a limiting value of γ corresponding to a cutoff period above which damping occurs. As C decreases, γ increases, and the period decreases. For C close to V_1 the periods become infinitely small. The group velocity in the second branch is distinguished by the occurrence of both a minimum and maximum value. Higher modes of propagation exist in the second branch, the periods corresponding to a given value of C decreasing with increasing mode number n. It is expected that the higher modes will in general have smaller amplitudes, one reason being that the shorter periods associated with these modes are more susceptible to irregularities of the bottom and are readily damped. There are n antinodal planes for vertical displacement (nodal planes for pressure or horizontal displacement) in the liquid layer beneath the free surface. The locations depend on the period and occur at the depths $y = \pi/\xi^{(n)}, 2\pi/\xi^{(n)}, \ldots n\pi/\xi^{(n)}$.

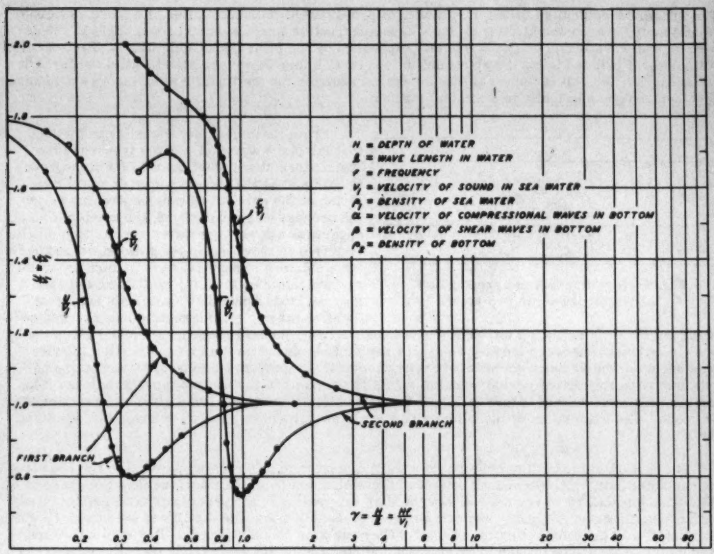

Fig. 5--Phase and group velocity curves for normal mode propagation in a system consisting of a liquid layer overlying an infinitely thick solid

Application of theory to microseisms

Transfer of energy at the sea surface--In a previous section it was shown that the sea surface is an antinode of vertical displacement for compressional waves of all periods for all modes of vibration of the system consisting of the ocean and the bottom. To set up vibration in any acoustic system the driving force should be applied at an antinode. Hence the free surface of the ocean is the proper place for application of force for exciting the normal modes of vibration of the system.

Failure to appreciate this point has been the chief obstacle in several previous attempts to explain the production of microseisms. BANERJEE [1935] convinced that microseisms originated at the storm center, made several attempts to show how the energy of surface gravity waves could be transferred to the ocean bottom in deep water, despite the exponential decrease in amplitude with depth. WHIPPLE and LEE [1935] recognized "that waves of two types can be propagated; these are practically the same as (1) the surface waves of the ordinary theory, and (2) waves of compression traveling obliquely through the water with the velocity of sound." They showed that appreciable forces could be transmitted to the bottom by compressional waves, but they did not consider the water and the bottom as forming a single acoustic system giving normal mode propagation.

SCHOLTE [1943] gave the theory for the combined effects of gravity and compressibility in a layer of water in contact with an elastic solid bottom. He then ruled out the gravity waves and deduced the phase-velocity curve for normal mode propagation. Using a ratio of 10^{-4} between the amplitude at the surface of compressional and gravity waves produced by the same wind, he concluded that the amplitude of ground motion corresponding to surface waves one meter high is of the order of 100 microns for a granite bottom. Scholte's emphasis, however, was not on propagation, but on the problem of transferring energy from the atmosphere to the ocean bottom. Hence he did not calculate or discuss the group velocity, although he did prepare an excellent tabulation of phase velocities in the first branch for a granitic bottom from his period equation. Scholte was apparently unaware that Stonely had previously obtained the same period equation and he failed to see the relation of group velocity to the microseism problem.

Propagation across deep water--It was shown that the propagation of elastic waves in a system consisting of the ocean and the bottom is dispersive. A disturbance at the free surface can be analyzed into simple harmonic waves having a continuous distribution of periods, each period traveling with its proper group velocity. The sequence of arrivals at a given point can be determined from the group-velocity curves, such as those of Figures 1 and 5, depending on whether the bottom can be considered as a liquid or solid.

At a distant point the prevailing periods observed will be those associated with stationary values of group velocity. The predominance of these periods has been verified in experiments conducted in shallow water (see Fig. 3). Thus, any non-periodic distrubance such as an explosion within the water, or an impulsive force applied to the surface of the water over a sufficiently large area would appear after propagation across deep water as oscillatory waves with periods corresponding to stationary values of group velocity. These periods will depend upon the depth of the water and the elastic properties of the bottom, both of which will be taken as constant along the path.

For the depth 15,000 feet, which may be taken as typical of the oceans, the dominant periods have been computed using the graphs of group velocity given in Figures 1 and 5. Table 1 gives the results on the basis of the liquid bottom theory for various values of the ratio V_2/V_1. Table 2 is based upon the solid bottom theory for the case $\rho_2/\rho_1 = 2.5$, $\beta_2 = \alpha_2/\sqrt{3} = 2V_1$, which corresponds to a crystalline bottom for which the compressional and shear wave velocities are respectively 17,300 ft/sec and 10,000 ft/sec. The corresponding periods for any other ocean depth H' is obtained by multiplying the periods given in the tables by the fraction H'/15,000. The elastic properties of the bottom assumed for Table 2 are believed to be closer to reality than those assumed for Table 1. Independent lines of evidence indicate that crystalline rocks are more likely to occur at or near the bottom of the ocean basins than very thick sediments which behave acoustically as liquids. It is striking however that the periods derived in Tables 1 and 2 fall well within the range observed for microseisms.

Table 1--Periods associated with minimum values of group velocity according to liquid bottom theory for the case $\rho_2/\rho_1 = 2$, $V_1 = 5000$ ft/sec, H = 15,000 ft

V_2/V_1	U_{min}/V_1	γ_{min}	$T = H/V_1\gamma_{min}$
			sec
1.05	0.99	1.20	2.50
1.10	0.98	0.92	3.30
1.30	0.93	0.57	5.30
1.50	0.90	0.47	6.40
2.00	0.80	0.37	8.10
3.00	0.73	0.33	9.10

Table 2--Periods associated with minimum and maximum values of group velocity according to solid bottom theory for the case $\rho_2/\rho_1 = 2.5$, $\alpha_2 = \sqrt{3}\beta_2$, $\beta_2 = 2V_1$, $V_1 = 5000$ ft/sec, H = 15,000 ft

Condition	γ	$T = H/V_1\gamma$
		sec
$U_{min}/V_1 = 0.8$	0.33	9.10
$U_{max}/V_1 = 1.7$	0.49	6.10
$U_{min}/V_1 = 0.75$	0.98	3.10

The relative importance of the first and second branch in determining the periods and velocity of propagation of microseisms is an object of further study. A possible experimental way of attacking this problem would be to study the periods and travel times of waves originating at a distant explosion in deep water.

The manner in which the character of microseisms depends upon the length of the path of propagation across deep water is a subject requiring study of data which has not been available to the authors. From the experimental results obtained in shallow water and the theory given above it is expected that microseisms with short paths across deep water would exhibit less regularity and have a greater range of periods than microseisms having longer paths across deep water.

Another problem requiring further investigation is the origin of the groups so characteristic of microseisms. Are groups due to interference phenomena or is each group identifiable with an impulse at the source? In a previous section mention was made of experimental studies of sound propagation in shallow water and the satisfactory explanation of the observed data by the liquid bottom theory of Pekeris. In most of these experiments the bottom consisted of unconsolidated sediments with compressional wave velocities under 7000 ft/sec to a depth at least several times the thickness of the water layer. The fact that sediments of this nature behave acoustically like liquids in considered an important result of the shallow water experiments.

It is conceivable that microseisms can originate in storms centered over shallow water or land in regions where many thousands of feet of unconsolidated and porous water-saturated sediments overly a crystalline basement. In such regions the system of thick sediments covering a crystalline basement is acoustically similar to a liquid layer over a solid bottom. A possible example of a region of this type would be Florida and the surrounding coastal waters. On the other hand, microseisms of the type described earlier would not originate in storms centered over shallow water or land where crystalline rocks rise close to the surface.

Transfer of energy at a continental border--At the edge of a continent a transfer of energy occurs from the normal mode propagation characteristic of a two layer ocean-bottom system to Rayleigh wave propagation on land. The exact details of the energy transfer have not been worked out, but several conclusions are immediately apparent. When the wave system reaches the inclined or vertical interface which marks a continental border, elastic waves of all types will be produced. Rayleigh waves having the same period as the incident waves can be expected to receive a sizable portion of the incident energy. This follows from the results of an earlier section in which it was shown that the incident wave system can be considered as Rayleigh waves modified by the presence of an overlying liquid layer.

Geologic applications of the theory--According to the theory presented in this paper, the periods of microseisms depend upon the depth of water and the elastic properties of the bottom along the path of propagation across deep water. A study of the periods of microseisms originating in storms of known location will yield significant information about the elastic properties of the bottom of the ocean to a depth of the order of several times the depth of the water. The variation in periods of microseisms from a moving storm at a single station and from station to station is a useful index of changes in structure of the ocean bottom along the different paths of propagation. Microseisms can be used to compare the structures of different types of ocean basins and to study the transition from ocean to continent. Studies of this type require data giving, for the entire duration of the storm, the location of the storm center and the amplitude, period, and general character of microseisms as recorded at several stations. Additional information concerning changes of intensity of the storm along its track would be valuable. Such data have not appeared in the literature and have not been available to the authors.

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JET STREAM IN UPPER TROPOSPHERE AND CYCLONE FORMATION

Herbert Riehl

Abstract--In this report, cases of relatively straight westerly flow aloft are investigated in an attempt to find criteria that indicate under what circumstances cyclone formation will take place along low-tropospheric disturbances in such instances. It is found that pronounced cyclogenesis will occur mainly if the westerly current aloft is very strong and concentrated in a narrow latitudinal band, constituting a "jet stream."

The structure of the jet stream is discussed with particular emphasis on the tropopause region. Finally the suggested relation between jet stream and cyclone formation is illustrated with the period January 27 to 29, 1947.

Introduction--Formation of extratropical cyclones, for instance, over the Great Plains east of the Rocky Mountains, generally is known to take place in connection with pre-existing upper-air troughs. Such troughs may have great amplitude prior to cyclogenesis. There are numerous instances however when they are relatively weak. When such a weak upper-air disturbance moves eastward from the Rockies, an incipient low pressure center in the lee of the mountains will develop to great proportions in some situations, while in others it remains weak and insignificant. The strength of low-tropospheric frontal zones cannot be the factor which determines exclusively whether cyclone formation in such cases will occur or not. For frontal zones of greatest intensity have at times been observed to remain inactive for protracted periods, while on other occasions great cyclones have developed in weak boundary layers. It is therefore of interest to determine whether there are other criteria that suggest a mechanism for initiation of surface deepening in these situations in which the broad-scale flow pattern aloft is predominantly westerly.

Profiles of upper Westerlies--In an attempt to find such criteria, the strength of the Westerlies at 300 mb and 700 mb was computed daily from October 1946 to April 1947. Charts published by the United States Weather Bureau for ten and 13 km for 1941 and 1942 were also utilized qualitatively. The area covered by the computations was bounded by latitudes 30° N and 60° N, and longitudes 70° W and 130° W. It was not possible to obtain an accurate picture of the high-level currents over the oceans. Even over the North American continent the area utilized for computation at 300 mb had to be reduced on some days due to lack of data.

The wind calculations were made following the procedure used extensively in previous studies [see "References" at end of paper, ALLEN and OTHERS, 1940]. From analyzed charts the average height of each isobaric surface was determined at every fifth parallel (lat. 30°, 35°, etc.). This was done by taking the arithmetic mean of seven height values read at intersections of the parallels with every tenth meridian. From the average heights the geostrophic components of the zonal wind subsequently were computed for every interval of five degrees of latitude. As the calculations were restricted to relatively straight westerly currents, no correction for curvature was necessary. The six wind values thus obtained were then plotted on diagrams having wind speed as abscissa and latitude as ordinate. The resulting curves gave the meridional profile of the zonal wind. Numerous profiles along individual meridians complemented this analysis.

It is clear that wind profiles computed in this manner will have their greatest significance when the upper flow is nearly westerly, so that the profile at individual meridians will correspond rather closely to the mean profile. It is precisely this type of situation that is to be analyzed here. The mean profiles give a conservative summary of conditions over North America; conservative, because possible errors in soundings at some particular longitude are outweighed by the composite picture; conservative also, because such an averaging process tends to minimize the maxima and minima of the quantity averaged [CRESSMAN, 1948].

The objection may be raised that the computations extended over too short a period; that moreover this period, as noted by NAMIAS [1947] was characterized by abnormal circulation patterns. However, it is easy to find many comparable situations in preceding years. The features of the high-level wind field to be brought out here are thought to be a part of the mechanism of the general

circulation. While the frequency of occurrence of the cyclogenetic process will vary over any given region from year to year, the process itself evidently remains unaffected.

Characteristic wind profiles--During periods when a relatively straight westerly current prevailed aloft, three typical classes of wind profiles were observed:

(a) The lateral shear at 700 mb and 300 mb is small (see Fig. 1a), and the vertical shear between these two surfaces is also small. The atmosphere is as close to a baratropic state as will be observed during the colder part of the year. Low pressure centers that formed during such periods remained weak and insignificant.

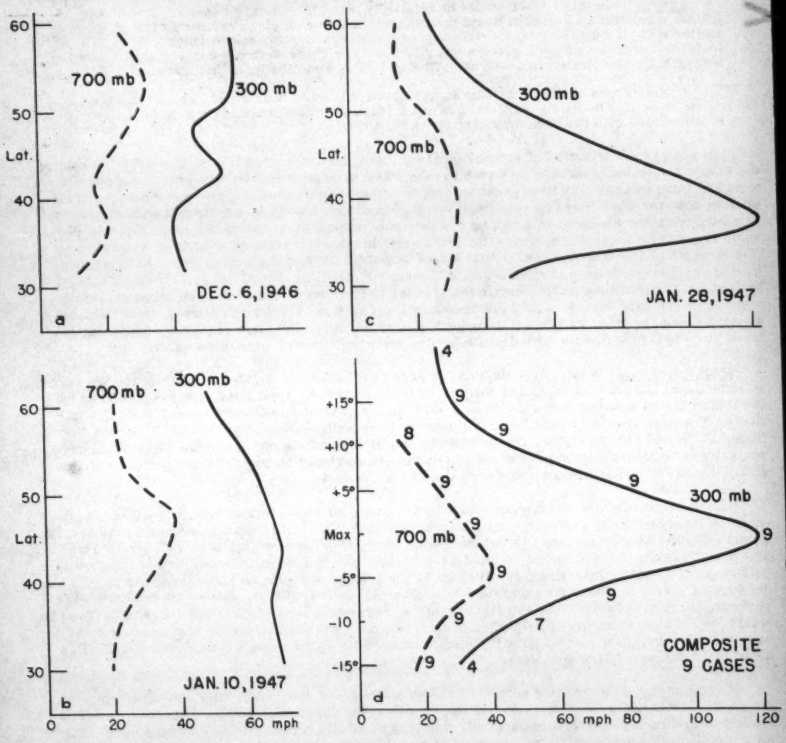

Fig. 1--Profile of westerlies at 700 mb and 300 mb, (a) December 6, 1946, 0300Z; (b) January 10, 1947, 0300Z; (c) January 28, 1947, 0300Z; (d) for nine cases with pronounced jet stream, averaged with respect to wind maximum at 300 mb; ordinate gives distance from zone of wind maximum at 300 mb in degrees latitude; numbers along curves indicate number of observations

(b) The lateral shear at 700 mb and 300 mb is small (see Fig. 1b), but the vertical shear is considerably larger than shown in Figure 1a. The atmosphere is baroclinic but in such a way as to show a fairly uniform value of vertical shear at all latitudes. Low pressure centers forming under such circumstances move rapidly eastward without great intensification. They are warm, "high-index" cyclones [ROSSBY, OLIVER, and BOYDEN, 1942].

(c) The lateral shear at 700 mb is small, but it attains large values in a narrow latitudinal band at 300 mb (see Fig. 1c and 1d). Both cyclonic and anticyclonic shear at that surface become very great, and between these two shear zones the zonal wind reaches sharply defined maxima. It may bear the name "jet" in these situations. The vertical wind shear also attains maximum values where the jet is located, while north and south of the jet it is small. Thus the horizontal wind shear in the high troposphere and the vertical wind shear through the troposphere are concentrated in a narrow zone. Within this zone, the atmosphere is strongly baroclinic. Outside of this zone, both to north and south, it tends toward a quasi-barotropic state.

When a jet stream of this kind became superimposed on a pronounced frontal zone or other perturbation of the low troposphere, intense cyclogenesis ensued. It is easy to establish the connection between such observations and theoretical investigations considering the relation between cyclone formation and strength of the vertical solenoid fields. But the observed solenoid fields primarily are not those connected with fronts situated between two airmasses characterized by different radiational history. The solenoid fields associated with jet streams are located mainly above the polar front, and they extend to the tropopause. The dynamics of generalized baroclinic westerly currents, especially the problem of stability of waves of small amplitude superimposed on such currents, has been the subject of extensive theoretical research. The most recent and comprehensive paper on this topic is that by CHARNEY [1947] which in many respects is an extension of the work of BJERKNES and HOLMBOE [1944] and which applies the ROSSBY [1939] formula for barotropic waves to a baroclinic atmosphere.

As an example, Figure 2a shows temperatures and potential temperatures in vertical cross section extending from Bismarck, North Dakota to Brownsville, Texas. The situation follows that illustrated in Figure 1c by one day. A pronounced frontal zone and attendant solenoid field are present. Most of the solenoids, however, lie above the frontal layer. Figure 2b indicates the relation between isentropes and lines of constant geostrophic west wind speed. These lines were computed from Figure 2a by the same methods employed by other authors. Calculations were greatly facilitated through use of the transformations of the hydrostatic equation by BELLAMY [1945]. The jet is centered above the low-tropospheric portion of the front, and therefore is located far south of its high tropospheric section. The strongest winds occur in the tropopause break. Most of the vertical increase of wind takes place above the frontal surface, and the lines of equal speed show that the principal current is confined to a narrow latitudinal band.

The westerly jet should be observed primarily in situations in which the wave length in the westerlies at 700 mb (and presumably throughout the troposphere) becomes abnormally long, demanding a basic readjustment of the long wave pattern [see also CRESSMAN, 1948]. This held true in 14 out of 16 cases with pronounced jet during the period October 1946 to March 1947. In these instances an increase of the wave number occurred coincident with or following within a day a jet stream peak. It may therefore be suggested that the formation of jets and their reaction on the pressure- and windfield of the lower troposphere constitutes a mechanism for an increase of wave number. Concerning the mechanism of formation of jet streams and resulting mass displacements after the development of inertia instability, reference may here be made to two recent publications [ROSSBY, 1947; STAFF MEMBERS of the Department of Meteorology of the University of Chicago, 1947].

Structure of jet stream--Jet streams such as shown in Figures 1c and 2b build gradually over a period of two to three days. The increase of wind speed is usually first observed at the Pacific Coast, from which it proceeds eastward. There are also indications of acceleration over the Continent. Finally, the current covers the entire country, and apparently extended also into the east Pacific and west Atlantic Oceans, or even larger areas. During the period of strengthening the west wind profile at 300 mb varies as illustrated in Figure 3a. At peak intensity the meridional wind shear attains and sometimes exceeds the theoretical values given by Rossby.

Figure 3b shows a 300-mb chart when the jet has attained full development. The contour lines are crowded along the jet, and their spacing increases northward and southward from the zone of strongest winds. There is still a meridional temperature gradient directed northward, so that the level of maximum speed of the current must be located above 300 mb. In this instance the highest wind speeds occurred near 250 mb (see Fig. 7b). The strongest winds were observed at variable

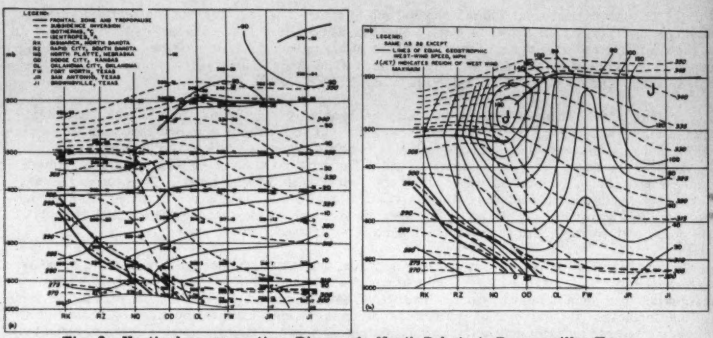

Fig. 2--Vertical cross section, Bismarck, North Dakota to Brownsville, Texas January 29, 1947, 0300Z, (a) showing isotherms in °C; (b) showing lines of equal geostrophic west wind speed in mph

elevations between 300 mb and 200 mb during the winters of 1946 and 1947. In view of what is climatically known on tropopause heights and temperatures in the upper troposphere, a good average value for the height of the center of the jet stream probably is 250 mb in the colder season.

Upper wind observations show the highest speeds in the region where the contour lines are most crowded, but these speeds are lower than those computed from the radiosonde data. At 500 mb many rawins indicated nearly the same speed as those at 300 mb. In a baroclinic atmosphere this is obviously not possible, and the discrepancy between computed and observed winds must be ascribed to the acknowledged difficulties with rawin measurements at low elevation angles. Computed wind profiles for different elevations (see Fig. 3c) show the increase of wind speed through the troposphere. The greatest increase occurs above 500 mb, in accord also with the vertical distribution of wind speed given in a recent article of OLIVER [1947].

At 200 mb the wind is slightly less than at 300 mb, and the latitude of maximum wind is to the south of that at 300 mb. The temperature field at 200 mb (see Fig. 4a) shows that at that elevation very cold air lies just south of the latitude of maximum current at 300 mb and very warm air to its north. Therefore, the strength of the jet must be decreasing rapidly upward through the 200 mb surface and the latitude of maximum wind must shift southward. South of the jet we are in the troposphere and to its north in the stratosphere. The wind maximum is situated where the tropopause slope is greatest, or where a double tropopause appears, in accord with classical concepts. This may be seen from Figure 4b, which gives contours of the tropopause and potential temperatures at the tropopause.

Further analysis of conditions above level of strongest current: Tropopause--The tropopause observed in the vicinity of the jet, especially to its south, corresponds neither to models of "arctic" nor "tropical" tropopause advanced in earlier writings. A tropical tropopause usually is located well above the 125-mb surface and potential temperature at this tropopause exceeds 360° A. On January 28, 1947, the only indication of such a tropopause existed at San Juan, Puerto Rico, where at a pressure of 125 mb and a potential temperature of 366° A the tropopause had not yet been reached, a normal occurrence there. In contrast, the tropopause located just south of the jet stream is found at a much lower elevation, but at about the same low temperature as the tropical tropopause. Therefore, it must be considered as an entirely separate, though very frequent type of tropopause formation.

This tropopause attains its maximum elevation just south of the jet. From there its height slowly decreases southward (see Fig. 4b), and in some instances remains at nearly constant height. Thus there is a suggestion, that in many situations the tropopause does not rise gradually equatorward from middle latitudes, but that there is a region of double tropopause formation in the subtropics and outer tropics with average location perhaps near latitudes 20° to 30°.

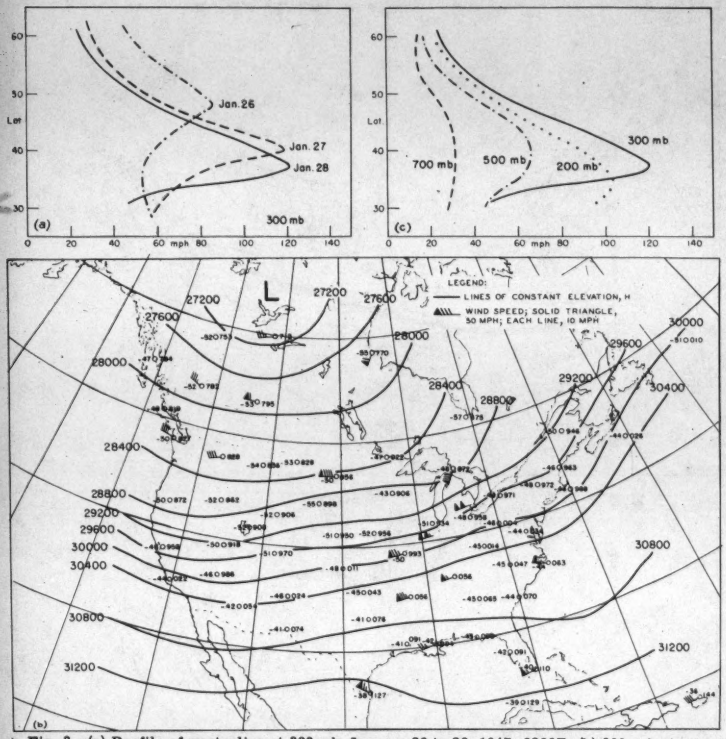

Fig. 3--(a) Profile of westerlies at 300 mb, January 26 to 28, 1947, 0300Z; (b) 300-mb chart, January 28, 1947, 0300Z; (c) profile of Westerlies at 700, 500, 300, and 200 mb, January 28, 1947, 0300Z

Northward from the zone of maximum elevation, the middle latitude tropopause slopes downward very steeply across the jet stream, as stated before. In an elongated band, situated fairly parallel to the jet near the United States-Canadian Boundary, tropopause heights are the lowest on the map. In some sections of the map (see also Figs. 2b, 6b, and 7b) the zone of lowest tropopause is characterized by a separate tropopause formation at much lower potential temperatures.

North of this zone, however, tropopause heights again increase, together with a lowering of tropopause temperature. Thus highest and lowest tropopauses closely adjoin in bands flanking the jet stream on both sides. The presence of a configuration of this type is essential, if there is to be a level at which the westerly current attains maximum speed. But the non-linear distribution of tropopause height and potential temperature demonstrate that horizontal displacement of air across latitude circles cannot be responsible for the observed configuration. The cause for the existence of the jet stream therefore cannot be sought in the tropopause configuration and in characteristic temperature differences at high levels between air of high and low latitudes. The tropopause configuration must be due to a vertical circulation above the center of the jet. This vertical circulation must be a compensating circulation, as postulated by Rossby so that the strength of the westerly current can decrease with elevation in the stratosphere. South of the jet stream, in the region of maximum tropopause elevation, there is ascent above the level of strongest winds. In the tropopause depression north of the jet there is descending motion.

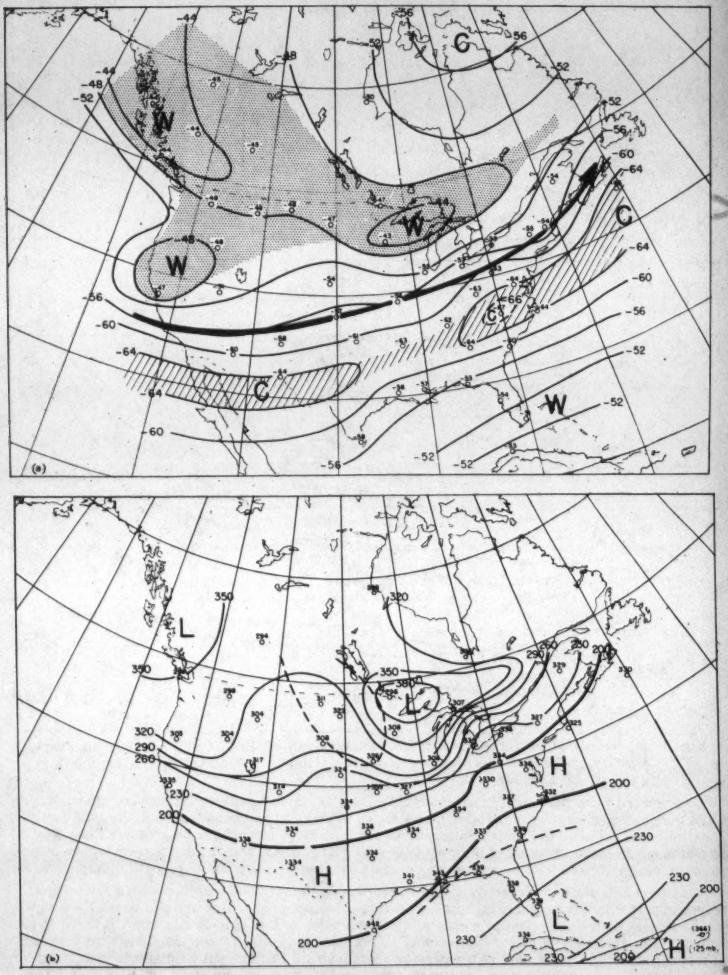

Fig. 4--(a) Isotherms (°C) at 200 mb, January 28, 1947, 0300Z; heavy covered arrow indicates center of jet; (b) configuration of tropopause (mb), January 28, 1947, 0300Z

Further analysis of conditions above level of strongest current: Meridional temperature gradients--The preceding conclusions may be verified further by considering the meridional temperature gradients observed above the level of strongest wind. At 200 mb (see Fig. 4a) a linear

meridional temperature gradient is not in evidence. But there are large temperature variations from north to south, and these variations have an entirely non-linear character. The coldest temperatures, by far, occur in a narrow band stretched parallel to the jet stream across the south central United States (cross hatched area on Figure 4a). From that band rapid warming takes place, both northward and southward. Temperature differences between the cold mid-latitude air and the tropical current amount to 15°C, and in extreme situations have attained 20°C and more. It is normal in winter to observe much colder temperatures at 200 mb near latitude 35° than at latitudes 15° and 20°.

The warmest temperatures on the map are found to the north of the jet, similarly arranged in an elongated band (dotted area in Fig. 4a). It may be noted that these temperatures are not very different from those characteristic for the tropical current. From that band northward there is renewed, appreciable cooling, at least over the eastern part of the map. In correspondence to the tropopause configuration, coldest and warmest temperatures on the map occur in close proximity to the jet stream, as well as the strongest meridional temperature gradient at 200 mb. The feature of elongated bands is observed only when the high-level flow is nearly westerly over wide areas. In presence of large troughs and ridges aloft, the field of vertical motion associated with these disturbances is superimposed on that due to the jet stream, and the isotherm configuration at 200 mb breaks down into closed centers of warm and cold air. The insert on Figure 5b shows temperature at 200 mb plotted against latitude. The section chosen is along the 90th meridian, but the profile is representative for many meridians (see Fig. 4a). It brings out clearly the non-linear character of the upper temperature field.

Figure 5a gives tephigrams of several typical soundings in the vicinity of the jet. International Falls, Minnesota is located north of the jet, and there is also polar air in the low troposphere. The tropopause is very low and warm. At Omaha, Nebraska, we are near the center of the current. Two tropopauses are in evidence, and between 330 mb and 220 mb Omaha is colder than International Falls, Minnesota or Lake Charles, Louisiana. In contrast, the normal northward decrease of temperature is evident in the lower levels.

Figure 5b affords comparison between International Falls, Greensboro, North Carolina and Swan Island in the Caribbean Sea. Greensboro lies a little south of the jet stream, in the belt of coldest air at 200 mb. The Swan Island sounding is a January mean sounding, which was used because current data were not available. Because of the smallness of aperiodic temperature changes at Swan Island, however, the mean sounding may be taken as representative of synoptic conditions. The cold layer at Greensboro extends from 290 mb to 160 mb, and it is clear that this cold air cannot have reached Greensboro through horizontal advection from north or south. If advection from a tropical and a polar airmass source were operative exclusively, mid-latitude soundings should look as sketched in Figure 5c.

In that figure the soundings from Swan Island and International Falls are again reproduced as typical soundings from tropical and polar air. The two intermediate curves are hypothetical. They show temperature decrease northward in the troposphere, temperature increase northward at high levels. Intermediate is a level at which there is no meridional temperature gradient. The tropopause slopes steadily downward with increasing latitude.

Below the level at which the meridional temperature gradient reverses, southerly winds are accompanied by warming and northerly winds by cooling. Above that level the reverse holds. Figure 5c thus illustrates ideas concerning the mechanism of temperature changes at high levels that were prevalent at the time when aerological observations were first made, and when these observations were as yet very scanty and covered only a limited latitudinal belt. Largely because of the statistically positive correlation between pressure and temperature in the substratosphere and lower stratosphere, it was thought by a large group of meteorologists that disturbances mainly originated in those parts of the atmosphere, and that the behavior of lower levels represented compensating motion, so as to reduce the magnitude of the upper fluctuations toward the ground.

The very frequent, if not to say permanent, presence of a non-linear temperature field near 200 mb necessitates a revision of the viewpoint regarding the role played by the high-atmospheric currents, unless the argument of differences in radiational cooling between different latitudes is invoked. Both because of the large value of temperature gradients near 200 mb and the double reversal of gradient such reasoning evidently is not applicable. It follows that vertical motion must be primarily responsible for the observed temperature distribution near 200 mb, as suggested in the tropopause analysis. It follows also that these vertical motions must be generated in response to events at lower levels in the vicinity of the jet stream maximum if events in and above the ozone layer are discounted. If it were possible for the jet stream to attain a steady state, the

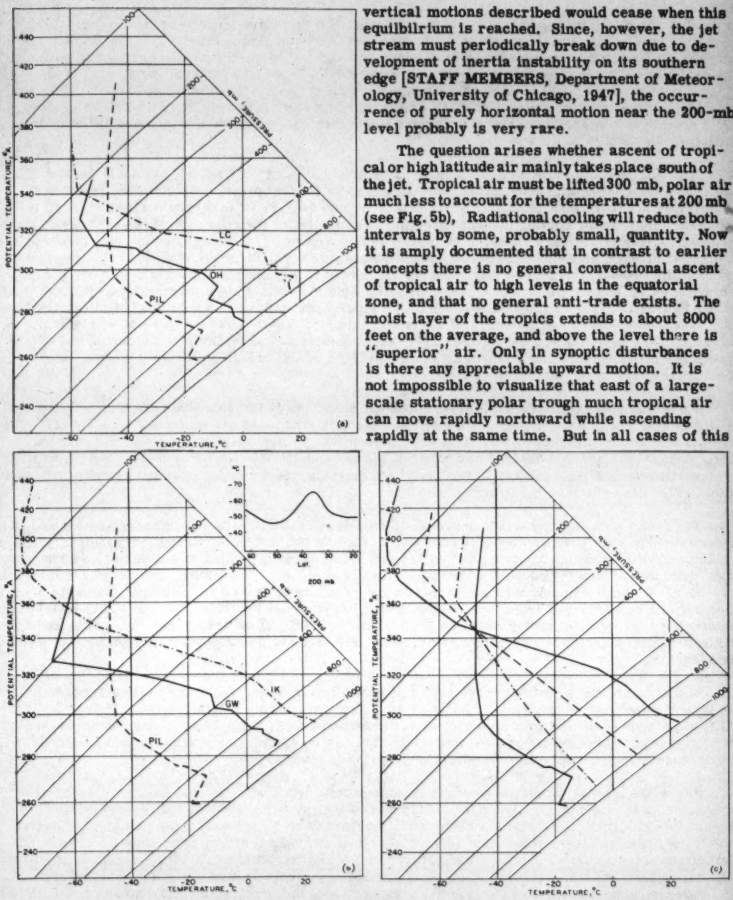

Fig. 5--Tephigrams (a) at International Falls, Minnesota (PIL), Omaha, Nebraska (OH), and Lake Charles, Louisiana (LC), January 28, 1947, 0300Z; (b) at International Falls, Minnesota (PIL) and Greensboro, North Carolina (GW), January 28, 1947, 0300Z, and Swan Island (IK), mean sounding for January; insert shows relationship of temperature to latitude at 200 mb, January 28, 1947, 0300Z; (c) at International Falls and Swan Island as in (b) with two hypothetical soundings based on assumption of quasi-linear meridional temperature gradients

vertical motions described would cease when this equilibirium is reached. Since, however, the jet stream must periodically break down due to development of inertia instability on its southern edge [STAFF MEMBERS, Department of Meteorology, University of Chicago, 1947], the occurrence of purely horizontal motion near the 200-mb level probably is very rare.

The question arises whether ascent of tropical or high latitude air mainly takes place south of the jet. Tropical air must be lifted 300 mb, polar air much less to account for the temperatures at 200 mb (see Fig. 5b), Radiational cooling will reduce both intervals by some, probably small, quantity. Now it is amply documented that in contrast to earlier concepts there is no general convectional ascent of tropical air to high levels in the equatorial zone, and that no general anti-trade exists. The moist layer of the tropics extends to about 8000 feet on the average, and above the level there is "superior" air. Only in synoptic disturbances is there any appreciable upward motion. It is not impossible to visualize that east of a large-scale stationary polar trough much tropical air can move rapidly northward while ascending rapidly at the same time. But in all cases of this kind noted by the writer there was no evidence whatever of ascent in the order of magnitude required to account for the cold region at 200 mb. On the contrary, in the case of some stationary polar troughs, the northward moving current was very dry, in contrast to moving polar troughs.

It must be concluded, therefore, that generation of the cold air most probably takes place in westerly currents with a cross component of motion toward south, as suggested by Rossby [STAFF MEMBERS, Department of Meteorology, University of Chicago, 1947].

Cross sections, January 27 to 29, 1947--The sequence of events that took place in connection with the jet analyzed in the preceding sections, will now be shown in the vertical cross section Bismarck, North Dakota to Brownsville, Texas. On January 27 (see Fig. 6a), only a weak frontal zone is present in North Dakota.

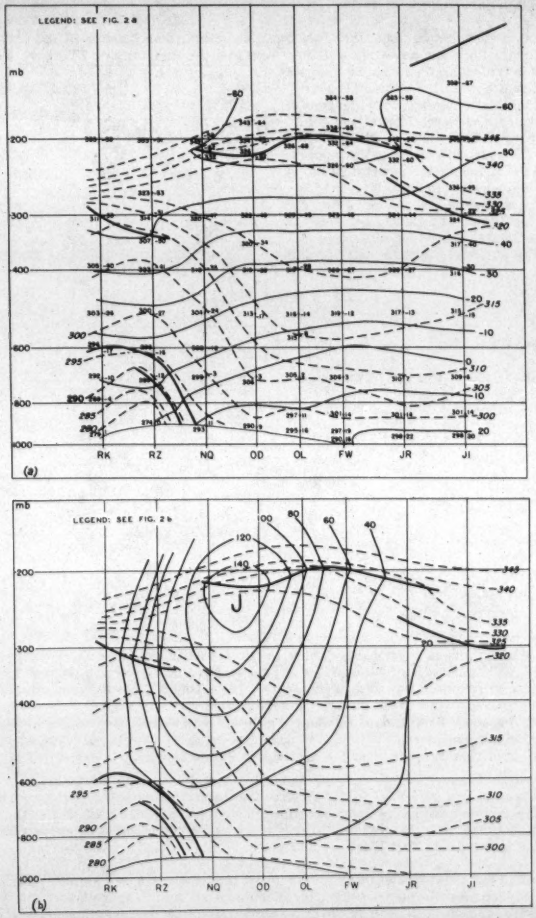

Fig. 6--Vertical cross section Bismarck, North Dakota to Brownsville, Texas, January 27, 1947, 0300Z, (a) showing isotherms in °C; (b) showing lines of equal geostrophic west wind speed in mph

Except for the surface layer, this zone is quite indistinct, and its existence above 800 mb may be disputed altogether. But there is a marked solenoid field, with concentration of solenoids near North Platte, while the warmest region on the section lies near Fort Worth and San Antonio. Turning to the wind profile (see Fig. 6b), we find that a well-marked jet is in evidence in the central United States. The existence of the jet thus is independent of the presence of a pronounced front. But the figure also shows the dependence of cyclogenesis on the presence of a disturbance in the lower layers, since no development took place in the west on January 27. Farther east, where the jet is superimposed on the front located in the Dakotas in our section, pronounced cyclone formation occurs.

In connection with this cyclone, the front sweeps southward on January 27, so that on the morning of January 28 it has advanced well into Texas on the surface (see Fig. 7a). But the solenoid field in the upper troposphere virtually has remained unaffected by this frontal movement. There is a little cooling with steepening of the lapse rate at North Platte (see Fig. 7c), while warming takes place at Brownsville suggestive of the vertical motion pattern postulated by STAFF MEMBERS, Department of Meteorology, University of Chicago [1947] for the atmosphere below the level of greatest velocities. The local concentration of solenoids is greatest in the frontal zone. But comparison of the number of solenoids in the frontal boundary and those above it demonstrates that the front still contributes only a fraction to the total increase of wind with height (see Fig. 7b). The jet stream lies in almost the same position as on the previous day and has nearly the same speed. For the United States as a whole, there was a slight increase (see Fig. 3a). Because of failure of the San Antonio sounding above 600 mb, the velocity distribution south of Fort Worth is uncertain.

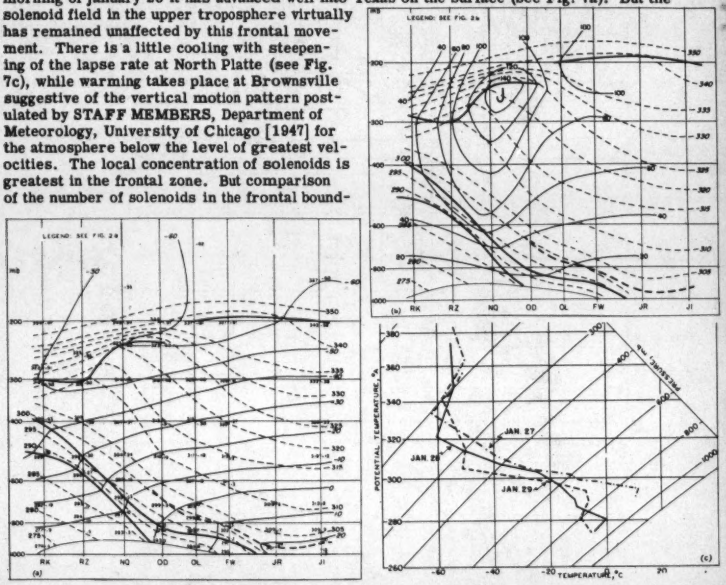

Fig. 7--(a) Vertical cross section Bismarck, North Dakota to Brownsville, Texas, January 28, 1947, 0300Z, showing isotherms in °C; (b) vertical cross section, Bismarck, North Dakota to Brownsville, Texas, January 28, 1947, 0300Z, showing lines of equal geostrophic west wind speed in mph; (c) tephigrams at North Platte, Nebraska, January 27 to 29, 1947, 0300Z; note advance of cold air in low troposphere, January 27-28, and retreat January 28-29, while in upper troposphere cooling, steepening of lapse rate and lowering of tropopause continue unabated throughout period.

Introduction of the front in the lower levels below the jet stream has significantly changed the outlook as compared with the previous day. Fronts as shown in Figure 7 frequently continue their motion southward over the Gulf of Mexico. Sometimes they become stagnant and degenerate. On some occasions they remain active and a new cyclone forms. In many cases the surface chart does not provide a good clue concerning which of these things will happen. The present analysis

suggests that superposition of the jet stream on the frontal zone, associated with an abnormally large spacing of waves in the Westerlies, constitutes a mechanism to initiate cyclone formation.

On the morning of January 29 cyclogenesis at the surface was fully under way, while deformation of the westerly current at high levels was only beginning. The well-marked polar front (see Fig. 2a) has retreated northward as a warm front, and in some sections its slope has decreased considerably during the change from cold front to warm front characteristics. A strong, low subsidence inversion now covers the country south of the front. The two solenoid fields, that connected with the front and that associated with the jet stream, are clearly separated. The solenoids connected with the jet have moved upward farther and are now located in the upper troposphere. In the middle troposphere, especially near North Platte (see Fig. 7c), the lapse rate has become very steep and approaches the dry-adiabatic. Thus the jet stream must have nearly attained its maximum possible speed, since the dry-adiabatic (or, in case of saturated air, moist-adiabatic) lapse rate sets the limit for development of horizontal temperature gradients due to vertical motion.

The jet stream (see Fig. 2b) is situated in the gap between lower and upper tropopause. Its position is unchanged, but its speed is somewhat greater than before. Percentually, however, the increase is slight. The relative barotropy of the air north and south of the jet is very evident.

The surface map for January 29, 0630Z, (see Fig. 8) shows the developing cyclone over the Rocky Mountains. The position of this center was coincident with the position of a new trough developing in the long wave pattern.

The front is of great intensity and extends east-west across the whole United States, roughly parallel to the jet stream. Large-scale frontogenesis has occurred in this front during the preceding day, and a widespread zone of precipitation is developing at map time, with heaviest precipitation oriented along the jet. There is evidence of great instability all along the frontal zone, and there are numerous attempts at wave formations. Such intensification is indicative of strong development. Although the moist layer advancing from the Gulf was restricted to the lowest kilometer, heavy precipitation and widespread thunderstorms developed under the jet. With surface

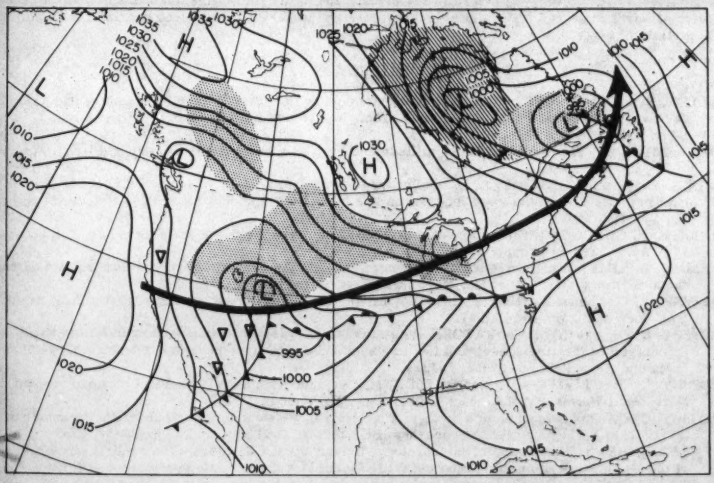

Fig. 8--Surface map, January 29, 1947, 0630Z; heavy covered arrow indicates center of upper jet stream; shaded areas are regions of steady and intermittent precipitation

temperatures near freezing, all precipitation forms from freezing rain to hail occurred in the Chicago area in heavy amount, as the cyclonic center was advancing rapidly northeastward from the Rockies while deepening strongly.

The preceding sections show clearly, as has also been observed in connection with many synoptic disturbances of lower latitudes, that the magnitude of rainfall associated with perturbations does not depend on the initial depth of the moist layer that is transported into the disturbed zone. On the contrary, the top of the moist layer lowered appreciably during the period January 27 to 29 in the southern United States and a temperature inversion formed, under influence of subsidence south of the jet below the level of maximum wind. Nevertheless, a deep moist layer was able to form within a few hours in the region of low-level ascent at the northern edge of the jet, demonstrating again that dynamic processes far exceed advective considerations in importance as regards the formation of rain.

Conclusion--The cyclogenesis January 28 to 29, 1947, was only one representative example of more than ten cases of similar cyclone formation during the winter of 1946 and 1947. One outstanding instance was the great deepening of April 5 and 6, 1947, associated with thunderstorms and floods. In that instance the jet had considerable anticyclonic curvature.

It is suggested that the jet stream appearing in connection with a pattern of very long waves in the Westerlies provides a mechanism for the initiation of cyclonic development and an increase of wave number. But it should be emphasized again that only one species of cyclone formation has been considered here, namely, that associated with initial westerly flow aloft, without pronounced streamline curvature. Nor is it suggested that the jet alone can create cyclones. It is evident that the jet is effective only if it is superimposed on a disturbance of the lower atmosphere. Clearly, the amount of cyclonic development to be expected depends in large measure on this factor. Therefore, when jet stream, long wave pattern, and low-tropospheric disturbance coincide in a favorable sense, ensuing cyclone developments will attain the greatest intensity.

Acknowledgment--This report contains details of the writer's contribution to the summary report on the general circulation in middle latitudes published in June 1947 [STAFF MEMBERS, Department of Meteorology, University of Chicago 1947]. The investigation was supported by the Office of Naval Research. The writer's thanks are due to Yi-Ping Hsieh who carried out most of the statistical work.

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THE USE OF RADAR IN DETERMINING THE AMOUNT OF RAIN FALLING OVER A SMALL AREA

Horace R. Byers and Collaborators

(Published contribution No. 3 of the United States Weather Bureau Thunderstorm Project)

Abstract--Radar storm echoes are compared with rainfall recorded by a battery of 55 sensitive rain gages located approximately one mile apart. For thunderstorms it is found that the areas of rainfall can be determined with accuracy by the radar. A single radar set can measure quantitatively thunderstorm rainfall that would be missed completely by existing rain-gage nets. If properly "calibrated" against a battery of rain gages, the radar can measure rainfall about as accurately as would be possible from a micronetwork of rain gages such as was used in these tests.

The usefulness of radar for detecting storms in areas of sparse synoptic observations and for locating local areas of precipitation that are too small to be "caught" in the synoptic net has been amply demonstrated [see "References" at end of paper; MAYNARD, 1945; BENT, 1946; REBER, 1946; SPILHAUS, 1946; BROOKS, 1946; WEXLER and SWINGLE, 1947; SMITH and FLETCHER, 1947]. Radar is now being put into routine use for detecting hurricane centers, thunderstorms, showers, and the details of precipitation associated with fronts and squall lines.

In addition to the use of radar in detection, meteorologists have visualized its possibilities as a quantitative meteorological instrument capable of measuring such quantities as, for example, the liquid and solid content of clouds or the amount of water precipitated over an area.

It is well known that the present distribution of rain gages in the United States is not dense enough to give a true picture of the amount of water falling on the land, particularly if the water is precipitated in the form of local showers or thunderstorms. If the density of the network were increased ten or even 100 times, we still would not be able to depict the details of rainfall from these small storms. Furthermore, the task of communicating synoptically the reports from such a tremendous number of rain gages would be physically impossible or, at least, impractical.

At the present stage of development of radar meteorology, one might well ask whether or not radar can be used instead of a battery of rain gages to obtain the true precipitation picture. Could a radar sweeping through an area, let us say, 50 miles in radius and thus covering nearly 8000 sq mi give us not only the location of thunderstorms but also the quantity of water deposited by them? One can visualize great benefits to be derived from such a system. In flood-warning or water-control operations for example, one could, if this method were successful, obtain immediately the distribution of water from thunderstorms in the small basins which result in sudden changes in water level or produce flash floods.

The correlations between radar echoes and rainfall given in the following pages show interesting possibilities even though obtained under circumstances in which the full potentialities of radar sets were not utilized. If the possible refinements had been introduced, better results would have been obtained. For example, variations in the setting of a calibrated gain control on the radar could have provided data on the intensity distribution of the rain by presenting different echo sizes for the same storm. Equipment and the necessary organization for these radar techniques were not available at the time and place of the observations. (A project of this kind has been undertaken in the All-Weather Flying Division, Air Materiel Command, by David Atlas, and further studies are being made by the Signal Corps, the Massachusetts Institue of Technology, and other organizations.)

The data from the 55 automatic rain gages located one mile apart and the continuously-photographed radar presentation in the Thunderstorm Project micronetwork in Florida in 1946, are used in this study. The rain gages, which were installed in this closely-spaced manner along with other meteorological instruments, were of the Ferguson weighing type, operated on a six-hour gear and with the sensitivity increased by increasing the mouth area 2 1/2 times. Thus, precipitation amounts as small as 0.01 inch could be measured with a time resolution of approximately one minute. From these records, maps showing isohyets of precipitation were drawn for every five minutes during thunderstorms.

The radar installation of the Army Air Forces, near Orlando, consisted of the MEW/CPS-1 long-range ten-cm wave length search radar, used for plan-position indication (PPI) of the thunderclouds and the so-called "beavertail" or AN/CPS-4, ten-cm range-height indication (RHI) radar. Thousands of photographs of sweeps of these radars through thunderstorms, many of which were over the rain gage net, were obtained. Figures 1 and 2 show an example of this triple representation of the rainfall for a selected storm, with the isohyets from the rain-gage stations in Figure 1, and the PPI radar scope and the RHI presentation in Figure 2.

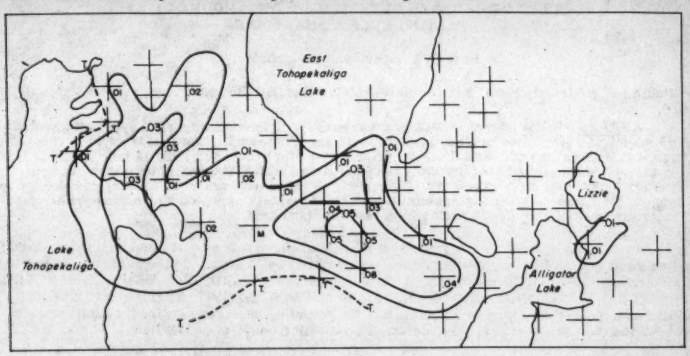

Fig. 1--Isohyets of five-minute rainfall amounts (inches) over the Thunderstorm Project micronetwork in central Florida, 15^h50^m to 15^h55^m EST, July 12, 1946; the stations are shown by crosses; the rectangle comprising the map is approximately 8 × 16 miles

Figure 2 is an example of the working chart used in the radar-rain correlation study. In the upper left is a tracing of the CPS-4 scope, with echoes, while in the lower left is a tracing of the CPS-1 (high beam) scope with echoes for the same time. The cross section shows the expanded CPS-4 echo, and underneath the cloud is indicated the limits of the surface-rainfall area and of the high- and low-beam CPS-1 echoes along the azimuth toward which the CPS-4 is pointing. A total of more than 100 cross sections were charted and studied in this way.

Before proceeding with the rainfall correlations, it should be explained that the CPS-1 radar had an antenna arrangement directed at two different elevation angles, a high-beam and a low-beam. Figure 3 shows the comparison of the areas of the high- and low-beam echoes. It demonstrates the expected result that there is a greater array of echo-producing clouds in the lower than in the upper levels of a thunderstorm. The high-beam echoes in practically all cases gave a better representation of the rainfall areas than the low-beam echoes.

Correlations--The areas within the high- and low-beam radar echoes and the areas of rainfall rates greater than approximately 0.01 inch per five min.were measured for a number of different days. This lower limit of rainfall rates was used because the rain gages could not reliably resolve amounts smaller than 0.01 inch and because all of the data were tabulated on the basis of five-minute periods. Where significant amounts falling at a lesser rate appeared on the autographic records over a longer period of time, the stations involved were in many cases included in the rain area. Most of the rainfall areas in these thunderstorms were sharp-edged; extensive areas of light rain were not present. A rate of 0.01 inch per five minutes corresponds essentially to the lower limit of moderate rain, defined by Weather Bureau Circular "N" as 0.11 inch per hour or more. In all, 12 storms consisting of 15 different rain areas and having a total of 100 five-minute time intervals were considered.

In Figure 4 the area of the high-beam echo is plotted against the area of rainfall (defined as above) at the same time. It is noted that in 85 of the 100 cases, the high-beam echo is larger than the rainfall area, although there are numerous cases of approximate correspondence. The data give a regression equation

$$A_{echo} = 3.11 + 1.27A_{rain}$$

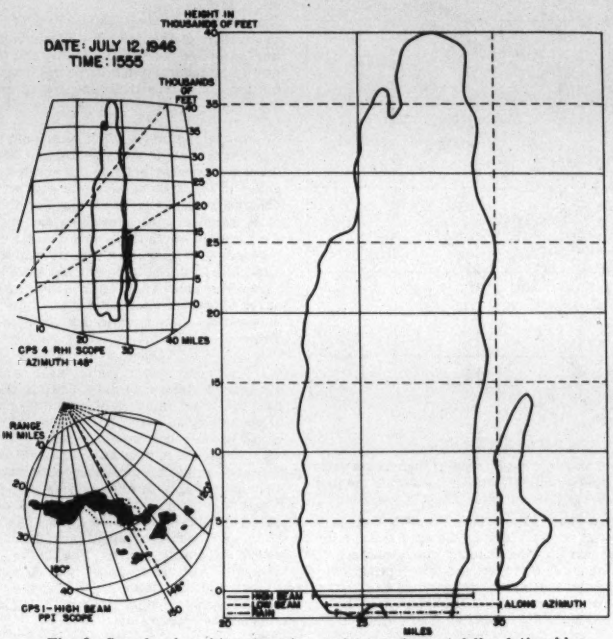

Fig. 2--Sample of working chart for studying radar-rainfall relationships

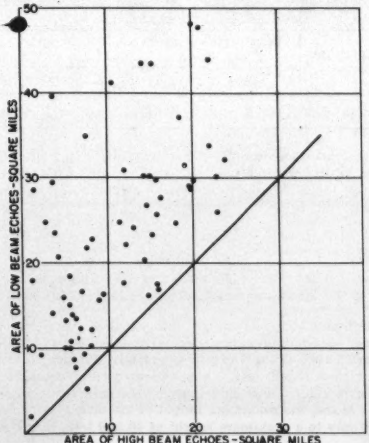

Fig. 3--Comparison of areas of low-beam and high-beam echoes

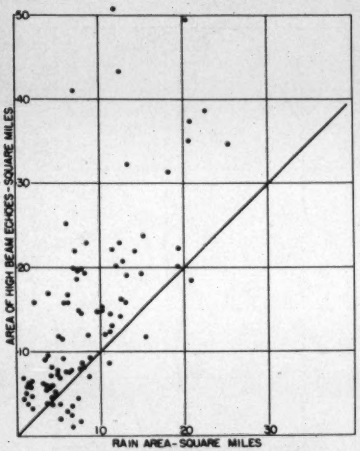

Fig. 4--Comparison of areas of high-beam echo and of rainfall occurring during the previous five minutes

with a correlation coefficient of 0.74. Both the probability of obtaining this slope from a population whose true slope is unity and the probability of obtaining this intercept from a population whose true intercept is zero are about 0.1.

In making this study it was found that there was a definite effect of the stage of development of the radar echo on the results. All cases in which there was rain with no radar echo were associated with dissipating storms from which an echo previously had been seen. All cases in which there was a radar echo of thunderstorm character with no rain were associated with building storms from which rain fell eventually. The frequency of these cases classified according to the time delay between echo and rain occurrence is shown in Table 1.

There were no cases of radar echo without rain in which rain did not fall to the surface within ten minutes of the initial appearance of such an echo. Also, there were no cases of rain with no radar echo in which the rain could not be associated with an echo which had disappeared within the previous ten minutes. This may simply be another way of saying that it takes the rain (as defined above) about ten minutes to reach the surface from where it is detected on the high-beam. Experience has indicated that an echo is not seen until the cloud extends at least to the freezing level. It may be assumed that the raindrops originate above but fairly near the freezing level. Taking the freezing level at about 15,000 feet, and the terminal velocity of large raindrops as about 1500 ft/min, it is found that the ten-minute delay noted can be easily attributed to the time required for the fall of such drops to the surface. It should be re-emphasized that, considering a ten-minute falling period, there were no independent cases of either rainfall or high-beam radar echo.

Table 1--Correlation of presence of surface rain and high-beam radar echo, based on 222 cases

Radar echoes with simultaneous surface rain centers	Radar echoes followed by rain in		Rain persists after disappearance of echo for	
	5 min	10 min	5 min	10 min
199	5	3	4	11

The building phases are taken into consideration by plotting in Figure 5 the area of the high-beam echo against the area of the rain ten minutes later. In this case there is better agreement between the two areas in the sense that there are fewer extreme departures from the regression curve which, in this case, is

$$A_{echo} = 3.15 + 1.01A_{rain}$$

The correlation coefficient is 0.75. The slope of the curve in this case is very nearly unity, but, as before, it is displaced in the direction giving echo area larger than rain area.

The maximum height of each echo, as shown on the CPS-4, was plotted against the maximum rate of rain observed at any station under that particular echo (see (Fig. 6). For the cases studied during the summer of 1946 in the vicinity of Orlando, Florida, there was no rain from a cloud echo with a top lower than 17,500 feet. In this locality the freezing level was below this altitude during the summer months. In all cases where the rainfall occurred at the rate of 0.20 inches per five minutes or more, the maximum height of the echo was at least 40,000 feet. Because the CPS-4 indicated only to a maximum height of 40,000 feet, this limitation was imposed on the data.

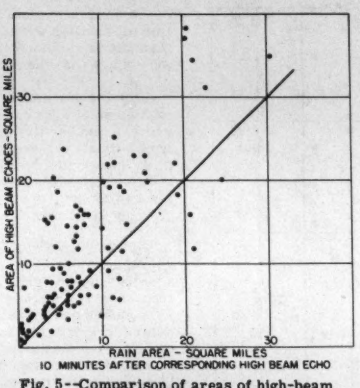

Fig. 5--Comparison of areas of high-beam echo and of rainfall occurring ten minutes later

Since the height of the CPS-4 echo gave a good indication of the intensity of the rain, a further study was made to determine if the CPS-4 echo could be used as a positive indication of the presence or absence of rainfall at the surface of the Earth. In the majority of cases observed, the CPS-4 echo reached to, and in most cases below, the zero altitude line as represented on the scope. This was apparently due to surface reflection phenomena. It was suggested that whenever the echo reached to or below the zero line, rain was falling from the clouds. With this criterion as a basis, an examination of 103 separate echoes from seven storms was made. In 66 cases where rain was measured at the surface, the CPS-4 continued to show an echo to more than 2000 feet below the indicated surface; in six cases of rain the echo continued from 1000 to 2000 feet below the surface. In 18 cases where an echo was returned with the beam center below the surface level, the storm was not over the network of surface recording stations and the presence of rain could not be substantiated. In ten cases where the base of the echo cut off above the surface, no rain was measured. The remaining three cases showed the base of the echo above the surface, but the associated rain pattern, if any, would have been off the network; thus, the presence or absence of rainfall could not be proved. Of the 103 cases examined, none was found which was not in agreement with the assumption that rain fell to the ground only when the CPS-4 echo reached to or below the surface.

All of these results indicate that with radar it is possible to determine quite accurately the areas of appreciable rain within the range of a ten-cm radar of this type. This is much better than could be done with the average spacing of rain gages in the United States, including cooperative stations, in dealing with storms of this size (diameter less than 18 miles, average 6 miles). The next part of the problem is to see what can be done with the radar in a quantitative sense.

Quantitative measurements--In the data presented thus far, the only quantitative representation is that of Figure 6 where the maximum rate of rain underneath the cloud is plotted against the highest point reached by the cloud echo top. It shows that when the cloud echo reaches 40,000 feet or higher (greater heights cannot be shown on the CPS-4), the rain falling out of the bottom may be expected to be quite heavy, with a maximum of about 0.20 inches per five minutes (2.4 inches per hour) or greater. This in itself is valuable information, and if the scope has been enlarged to show greater heights it might have proved even more helpful.

It should be pointed out that, since radar echoes from clouds depend upon the size and number of drops [RYDE, 1946; ROBERTSON and KING, 1946; MARSHALL, LANGILLE, and PALMER, 1947] echo intensity would be expected to give a measure of the water in the cloud and falling out of it. In the use of radars on the Thunderstorm Project in Florida provision was not made to measure the intensities. The scopes were "saturated" with echo in nearly all areas where rain was occurring and hence no measure of relative intensity was possible, except to a very limited extent. Since the surface micronetwork was spread out at approximately a constant distance from the radar, the effects of different ranges could not be investigated.

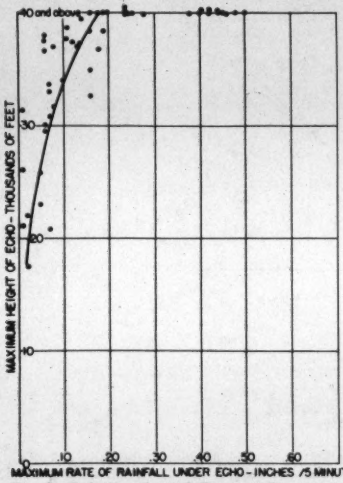

Fig. 6--Relation of rainfall rate at five-minute isohyetal center to maximum height reached by overlying storm echo

A number of plots of radar echoes against rainfall amounts were tried, showing only slight quantitative relationships. The following plots were made and studied:

(1) The successive sizes of the echoes along each azimuth were compared with the rainfall in corresponding five-minute periods at stations lying within a two-degree sector along each azimuth (range 20-30 miles). The rates of change of these echo sizes for the same cases were also checked against the rainfall. Neither of these plots showed a significant relationship.

(2) The depth of the CPS-4 echo below the zero line at a particular station was plotted as a function of time and the rainfall amounts in successive five-minute periods at the station were plotted on this same chart. These elements showed lack of correlation, although in each case examined the maximum five-minute rainfall amount at each station occurred from five to 12 minutes after the maximum depth of the CPS-4 echo.

(3) The depth to which the CPS-4 echo extended below the zero line was plotted along various azimuths in a single sweep of the radar. Isopleths for these depths were drawn and on this pattern was superimposed the isohyetal pattern for the five-minute period ending five to nine minutes after the sweep. A study of these charts indicated that the centers of depth of the CPS-4 echo and the centers of rainfall agreed fairly well in position, but there was no clear quantitative relationship.

(4) Further study of CPS-4 data was made by drawing area-depth curves for both the rainfall and the depth of the echo below the zero line. In all cases the areas were limited by a boundary drawn around the surface network one-half mile from the perimeter stations. This was done to eliminate the need for extrapolating the rainfall data. Marked similarity was noted between these pairs of curves.

(5) A final set of curves from CPS-4 data was drawn. For a given area, the depth of the rain and the depth of the CPS-4 echo were plotted against each other, with a separate curve for each area. The family of curves, shown in Figure 7 followed a consistent pattern but covered a very broad band and were of such a nature as to be insensitive at high values. Nevertheless the curves showed a quantitative relationship of the data.

(6) Rain depth per five minutes and the volume of the cloud echo at five-minute intervals were studied. For this purpose the volume of the echo was obtained by considering the echo as a solid with a uniform horizontal cross section equal to the area of the CPS-1 high-beam echo and a height equal to that indicated by the CPS-4 echo. Echoes that extended above 40,000 feet were considered to have a height of 40,000 feet only, an assumption imposed by the height limitation of the CPS-4 radar. Although in each case the maximum rainfall depth follows or coincides with a peak in the cloud volume, very little of quantitative value came out of these plots, as shown in the total data for each of four different storms plotted in Figure 8.

(7) Graphs of the percentage change in the average depth of the rain and the percentage change in the volume of the echo showed no consistent relationship.

Volume-time relationships--Good results were finally obtained by considering average volume conditions for an entire storm. A plot was made of the total volume of water deposited over the area against the average echo volume multiplied by the time in minutes over the area. The latter quantity was derived by determining the volume for each five-minute period that radar echoes appeared over the network and finding the arithmetic mean of these values. This average volume

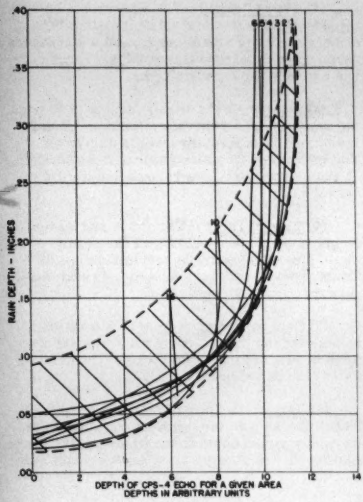

Fig. 7--Five-minute rainfall depth compared with depth of CPS-4 echo below zero altitude line; the curves represent different areas, in arbitrary units of 2.67 sq mi, the and cross-hatched area is an envelope of all observed values; note that the curves are of quantitative value for the smaller areas of rainfall and for rates of less than 0.15 in per five minutes

was then multiplied by the duration over the network (actually the rain duration). Again there was the limitation imposed by the CPS-4 radar which prevented volume computations for portions of the echoes above 40,000 feet. As before, the volume was obtained by multiplying the cross-sectional area as shown on the CPS-1 by the heights shown in the CPS-4 up to the limiting 40,000 foot height.

The result of this relationship for the nine storms for which the complete data were available is presented in Figure 9. The points appear to lie on a reasonably smooth curve.

This curve may be regarded as a "calibration curve" of this radar as a rain-measuring instrument over a basin of the general size of our micronetwork for Florida storms of the type here considered at a range of approximately 25 miles..

Since most of the storms for which CPS-4 photographs are available extended to 35,000 feet or more, it was felt that most storms in this part of Florida, during this season, extended to these heights. If the heights were all about the same, then area would be equally as good as volume in the cloud echo measurement. This would also provide more points for the calibration curve. A graph was plotted showing the mean or average area of the radar echo times the duration of the rain (minutes) over the network versus the volume of rain deposited over the network in each storm (see Fig. 10). This made it possible to include 21 more storms in the study. While there is a greater scattering of points plotted in this manner, a similar calibration curve is indicated. The two storms falling farthest from the curve were associated with frontal situations in contrast to the others which occurred with no fronts in the vicinity.

The curves are not exactly logarithmic, but when plotted on semi-log paper a straight line is approximated, as shown in Figures 11 and 12.

With these calibration curves it is possible, as shown here, to obtain a measurement of the total rainfall almost as reliable as that obtained from a network of recording rain gages spaced a mile apart over the area. It is surprising that the volume of a cloud should have such a close relationship to the amount of water which falls out of it. The number and size of the drops, strength of the vertical currents, and amount of lateral convergence into the cloud would determine the amount of rain. As shown on a preceding page, there is no quantitative relationship between cloud volume and rain instantaneously or over a five-minute period. It is only when conditions are averaged and integrated for the duration of the storm over the area that significant results are obtained. It is apparent that the factor of time greatly reduces the percentage of error.

Limitations of application--The calibration curves cannot be used without modification except under the same conditions as those from which the data have been extracted. There are important limitations as to the following factors:

(1) Region--To what extent these or similar curves are applicable to regions other than Florida is not known. Data from the Thunderstorm Project network in Ohio should soon give an answer to this question.

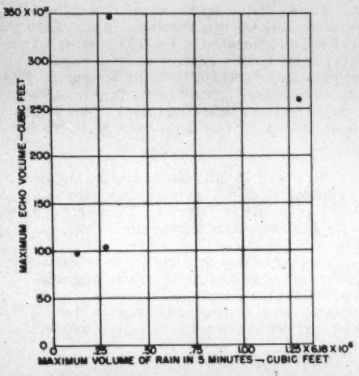

Fig. 8--Relation of maximum echo volume to maximum volume of water reaching the ground from the storm in a five-minute period, plotted for four storms

(2) Type of storm--The data cannot be applied to storms that are not of the same type. General cyclonic storms or frontal disturbances would show different relationships. These curves are only for thunderstorms.

(3) Season--In the winter months in Florida the rains are of a general cyclonic or frontal character. The freezing level is also lower. The prevailing drop sizes appear to be smaller. These storms would not be expected to fit the curves.

(4) Type of radar--The power and wavelength of the radar would affect the results as would also other possible peculiarities of different types of radar. Each type of radar would perhaps have to be calibrated.

(5) Gain setting of radar--The areas or volumes of the echoes would vary with variations in gain setting on the radar. The gain could also be calibrated.

(6) Range--The power returned by a target that is larger than the beam intercepting it, is inversely proportional to the square of the range. A different set of calibration curves would have to be made for every 25 miles, let us say, of range.

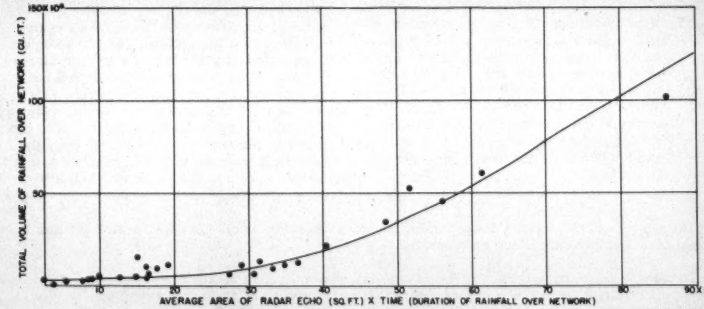

Fig. 9--"Calibration curve" of the CPS-1 radar in terms of echo volume for Florida thunderstorm observations

(7) Attenuation by intervening storm--The radar "sees" storms, one behind the other. The attenuation by the nearest storm would tend to reduce the echo size of the storm behind it. Corrections usually would have to be applied for this situation.

(8) Anomalous propagation--Evaporation of rain at the ground along the path of the radar beam produces a moisture stratification and temperature inversion which sometimes causes "channeling" of electromagnetic energy [COONS, 1947]. This guided propagation distorts the size of the echo and exaggerates the ground clutter so that it cannot be differentiated from cloud in many cases.

(9) True height of tops--The fact that good results were obtained even though the cloud tops could not be detected when they were above 40,000 feet, suggests that the volume of cloud above that height is not nearly as important in determining the total rain as is the volume at low and medium heights. When the areas alone were plotted without considering heights the results were

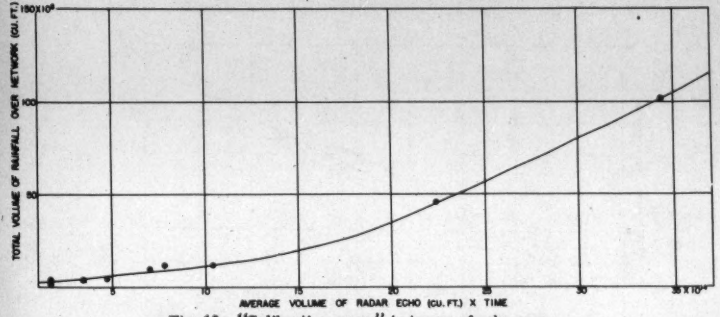

Fig. 10--"Calibration curve" in terms of echo area

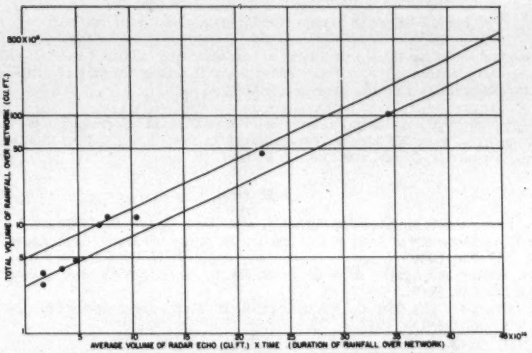

Fig. 11--Data of Figure 9 plotted on semilog coordinates

still good. (The radar did not receive echoes from clouds that did not extend to at least 15,000 or 20,000 feet). The data would have to be used with caution under conditions where the cloud tops are at a markedly different height from those encountered over central Florida in summer. The height of the freezing level would be important in determining this effect.

(10) Size of area--As the area of the network increased, the time that the thunderstorm would be over the area would become greater so that both the abscissa and the ordinate of the graphs would be affected in the same way. Whether or not the curves can be extended to cover significantly larger areas remains to be seen. In practice it would be advisable to divide a drainage system into small basins or parts of large ones to compute the flow of water from the atmosphere by this radar method.

Conclusions--The results show that rainfall over small areas can be determined by radar in a manner many times more accurately than is possible with existing rain gage distributions. (It is significant that there is no permanent rain gage in the network area of our temporary experimental installation in Florida.)

Quantitative results universally applicable have not been found from these limited experiments, but the way has been pointed for the use of radar to replace point rainfall measurements from widely scattered gages. Radars in each section of the country, for various seasons and storm conditions could be calibrated by means of this battery of rain gages placed at various ranges.

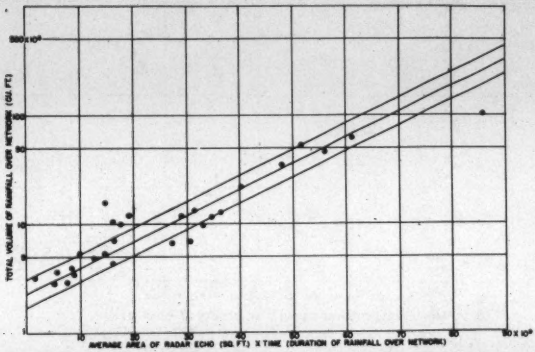

Fig. 12--Data of Figure 10 plotted on semilog coordinates

Eventually one can visualize the possibility of at last obtaining the exact rainfall picture from radars strategically located. Even a small radar set with a range of only 50 miles could sweep out an area to obtain rainfall details over nearly 8000 sq mi.

Acknowledgement--The principal assistants to the author in the research work and preparation of the manuscript were William A. Jenner, Harry L. Hamilton, Jr., John D. Bledsoe, Jr., Edwin C. Hull, Richard D. Coons, and Louis J. Batten.

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EVALUATION OF SEA-SURFACE ROUGHNESS FROM UNDERWATER-PRESSURE RECORDINGS

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(Contribution No. 407, Woods Hole Oceanographic Institution)

A total of 639 records of underwater-pressure fluctuations from Woods Hole vicinity off Cuttyhunk Island, Massachusetts, and 1022 records from Bermuda, has been evaluated in terms of sea-surface roughness. The Woods Hole (Cuttyhunk) records cover the period July 1946 to May 1947, with operational times of 20 minutes every four hours; and the Bermuda records, February to May 1947, with operational times 20 minutes every two hours.

Average and modal values of wave heights and wave periods together with standard deviations and probable errors are tabulated for each month. Relationships between the average wave height and period, average of the highest one-third waves, highest waves and wave steepness are also shown.

The study is preliminary and present results are intended to illustrate the type of sea-surface data to be obtained from recently developed wave-recording instruments.

Introduction

Underwater-pressure instruments, which automatically record pressure changes near the sea bottom, are in operation in the vicinity of Woods Hole (off Cuttyhunk Island, Massachusetts) and Bermuda. At both locations the pressure elements are located on the sea bottom (approximate depth 75 feet at Cuttyhunk and 120 feet at Bermuda) and electrically connected to onshore recorders by cable. The present operational schedule is a continuous 20-minute recording every two hours at Bermuda and every four hours at Cuttyhunk.

Records from these instruments are scaled for pressure wave height (ΔH_h) and wave period (T) at depth of instrumentation, h. The wave height at the sea surface (ΔH_s) is then computed by

$$\Delta H_s = 1.35 \Delta H_h \cosh 2\pi h/\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where

$$\lambda = gT^2/2\pi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In (1), the factor 1.35 has been experimentally determined at both instrument sites, by direct comparison of simultaneous near-bottom and surface-wave heights [see "References" at end of paper, SEIWELL, 1947 and SEIWELL (in press)]. Its probable error is 0.037.

A total of 639 records from Cuttyhunk and 1022 from Bermuda has been analyzed. In each case, two-minute intervals of each record were scaled for wave height and wave period and the average of each computed. On the basis of arrangements into monthly frequency distributions, the characteristic statistics computed are summarized in Tables 1 and 2.

The sea surface at Cuttyhunk and Bermuda

Wave height--Wave height and wave period appear as an inverse relationship, (see Fig. 1), such as would result from longer period waves being generated at such distances from the target that amplitudes are reduced during travel times to values lower than those of the shorter period waves of local winds.

The mean and mode of wave height do not coincide. The most frequently occurring wave heights (indicated by modal values) during any month, are lower than the average monthly wave heights. The difference between mean and mode becomes more for greater wave heights. Thus,

Table 1--Summary of statistical properties of monthly sea-surface conditions at Cuttyhunk

Month	No. of obs.	Sea surface wave height				Bottom wave period			
		Average	Mode	Standard deviation	Probable error	Average	Mode	Standard deviation	Probable error
1946		ft	ft	ft	ft	sec	sec	sec	sec
July	78	1.42	0.67	1.18	0.09	7.99	7.73	1.10	0.08
August	64	1.86	0.99	1.23	0.10	7.73	7.70	1.09	0.09
September	72	0.92	0.56	0.83	0.07	9.51	9.60	1.94	0.16
October	104	1.55	0.70	1.49	0.10	8.62	6.74	1.83	0.12
November	97	1.68	0.93	1.38	0.09	8.22	6.81	1.42	0.10
December	81	3.75	1.09	2.65	0.20	7.46	6.73	1.28	0.10
1947									
March	30	1.12	0.70	0.81	0.03	9.65	8.83	1.80	0.22
April	80	1.42	0.63	1.34	0.10	8.29	8.20	1.37	0.10
May	33	1.27	0.41	0.95	0.11	7.84	6.72	1.95	0.23

Table 2--Summary of statistical properties of monthly sea-surface conditions at Bermuda

Month	No. of obs.	Sea surface wave height				Bottom wave period			
		Average	Mode	Standard deviation	Probable error	Average	Mode	Standard deviation	Probable error
1947									
February	133	1.86	0.80	1.60	0.09	9.63	9.73	0.92	0.05
March	335	1.43	0.77	1.08	0.04	9.58	9.24	1.28	0.05
April	305	0.80	0.70	0.45	0.02	9.83	9.30	1.35	0.05
May	249	0.82	0.71	0.40	0.02	10.33	9.31	1.43	0.06

at Cuttyhunk, where average wave height increased from a value of 0.92 feet in September to 3.75 feet in December, the mode increased from 0.56 to 1.09 feet, a two-fold change in mode compared to a four-fold change of average wave heights. Similarly, at Bermuda, a maximum average wave height of 1.86 in February and a minimum of 0.80 in April had corresponding modal values of 0.80 and 0.70 feet. Thus, winter increases in general roughness of the sea surface are significantly less than increases in average wave height, and the mode is of greater operational value than the average. In forecasting sea-surface roughness, mode and average need be distinguished.

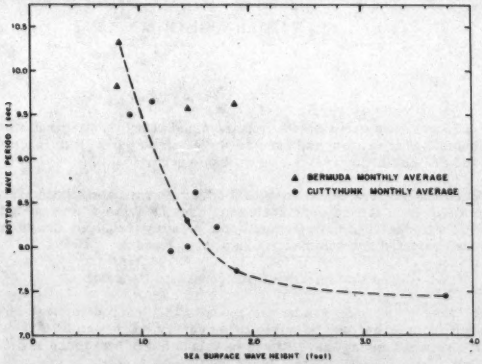

Fig. 1--Relationship of average monthly surface wave height and average bottom wave period for Cuttyhunk and Bermuda

Average wave heights at Bermuda and Cuttyhunk do not differ greatly. During the comparable months of March, April, and May 1947, the average for the former was 1.03 feet compared to 1.27 feet for the latter; modal values were 0.72 and 0.58 feet, respectively. It is indicated that higher seas persist later in the spring along the New England coast.

Wave period--The modal and mean values of bottom wave periods are more nearly equal than in the case of wave heights. Tables 1 and 2 show that the maximum average bottom period of 9.65 in March corresponded with a mode of 8.83 and the minimum average of 7.46 seconds in December had a mode of 6.73. Periods of surface waves are to be expected to be lower than those recorded at or near the bottom. On the basis of simultaneous surface and near-bottom observations in 1946, it was estimated that at depth of instrumentation, the average period at Cuttyhunk was about one-half that occuring at the surface, and at Bermuda about one-third. The average bottom period represents an upper limit for the average surface period.

Relationship of average surface wave height to average of highest one-third waves

The basic measurements of wave heights and wave periods on the records were used to compute averages of the highest one-third waves. These values of greater wave heights are of more operational value than averages of all wave heights in that higher waves dominate conditions during any time interval. Also, it appears that, in visual recordings of waves, it is the highest one-third which is observed, rather than the infinite detail making up the average pattern of the sea surface.

Relationship between average sea surface wave heights and average of the highest one-third waves for Cuttyhunk and Bermuda is illustrated by Figures 2 and 3. The linear relationship is considered significant. For both sets of data, independent fits by least squares give identical results, namely: Average highest one-third waves = 1.57 (average wave height).

Relationship of average wave height to wave steepness

Wave steepness is defined as the ratio of wave height to wave length. It appears to be related to the stage of development of the wave when the latter is expressed as the ratio of wave velocity to wind velocity [U. S. HYDROGRAPHIC OFFICE, 1944].

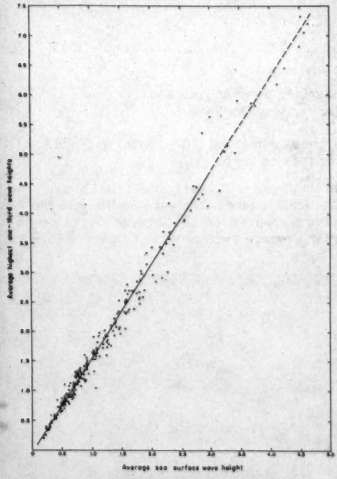

Fig. 2--Relationship average sea-surface wave heights and average highest one-third surface waves, Cuttyhunk

As waves move into shallow water, wave steepness takes on an added significance in that the crests become narrower and steeper after they begin to feel bottom. Thus a shallow-water steepness and a deep-water steepness are distinguished, and the ratio of the two is a characteristic factor in sea-surface conditions.

The critical depth at which wave velocity c is theoretically determined by depth of water h, rather than by length of the wave itself λ, is derived from the basic equation

$$c^2 = gL/2\pi \tanh 2\pi h/\lambda$$

When the ratio of depth to wave length becomes 0.4, deep-water waves begin transformation into shallow-water types. Thus for depth of instrumentation at Cuttyhunk (75 feet), wave lengths above 188 feet (approximately six sec) are affected; and at Bermuda (120 feet) those above 300 feet in length (approximately 7 1/2 sec) are altered. From data in Tables 1 and 2, longer waves occurring at both locations may possibly be expected to have undergone some transformation of their deep-water characteristics.

Wave steepness, as computed for our purposes, is taken as the ratio of average surface wave height to average bottom period. Since the average bottom period represents an upper limit of average surface wave period, the actual average steepness of sur-

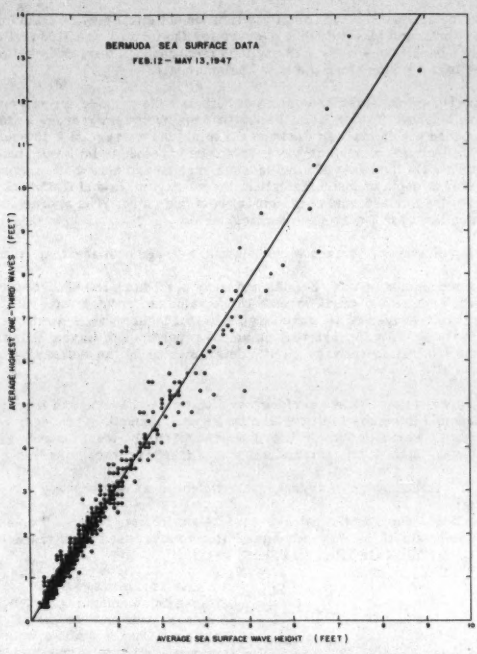

Fig. 3--Relationship average sea-surface wave heights and average highest one-third surface waves, Bermuda

face waves is several times higher. Nevertheless steepness computed in this manner from available records possesses a significance in characterizing the sea surface.

The average values of sea surface wave heights in intervals of 0.5 feet (see Table 3) are plotted against per cent of wave steepness in Figure 4. The least-square straight line fitted to the 900-odd Bermuda values has the equation: Average wave steepness = 0.286 (average wave height) - 0.06. Comparison of computed and observed values for average surface wave heights of 0.04 to 5.41 feet is given in Table 3.

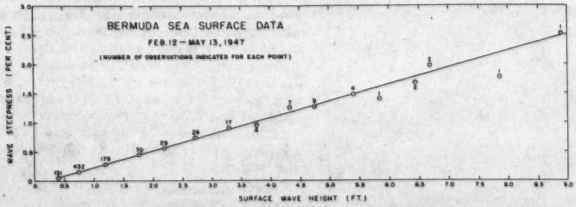
BERMUDA SEA SURFACE DATA
FEB. 12 – MAY 13, 1947
(NUMBER OF OBSERVATIONS INDICATED FOR EACH POINT)
WAVE STEEPNESS (PER CENT)
SURFACE WAVE HEIGHT (FT.)

Fig. 4--Relationship average sea-surface wave heights and average wave steepness, Bermuda; the straight line has the equation: Average wave steepness = 0.29 (average wave height) - 0.06

Table 3--Comparison of observed and computed average wave steepness at Bermuda

Height interval	Average surface wave height	Observed average steepness	Computed average steepness	Difference
ft	ft	pct	pct	pct
0.00-0.50	0.40	0.06	0.06	0.0
0.51-1.00	0.74	0.15	0.16	+0.01
1.01-1.50	1.20	0.28	0.29	+0.01
1.51-2.00	1.76	0.45	0.45	0.00
2.01-2.50	2.19	0.56	0.57	+0.01
2.51-3.00	2.72	0.74	0.72	-0.02
3.01-3.50	3.29	0.91	0.89	-0.02
3.51-4.00	3.77	0.96	1.02	+0.06
4.01-4.50	4.32	1.25	1.18	-0.07
4.51-5.00	4.74	1.27	1.30	+0.03
5.01-5.50	5.41	1.48	1.49	+0.01

Operational surface wave height patterns

On the basis of data analyzed in this fashion, selected statistical parameters may be arranged in patterns of operational value. One type is illustrated by Figure 5, where monthly variations in height limits of significant waves are shown for 50 and 75 per cent time limits.

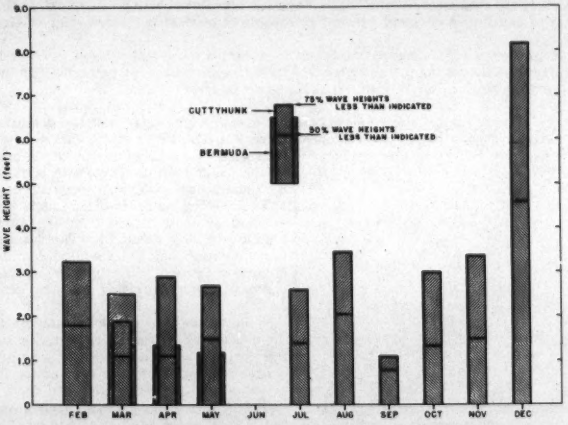

Fig. 5--75 and 50 per cent occurrence of average highest one-third surface waves, Bermuda (February to May 1947) and Cuttyhunk (July to December 1946, March to May 1947)

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THE WESTWARD INTENSIFICATION OF WIND-DRIVEN OCEAN CURRENTS

Henry Stommel

(Contribution No. 408, Woods Hole Oceanographic Institution)

Abstract--A study is made of the wind-driven circulation in a homogeneous rectangular ocean under the influence of surface wind stress, linearised bottom friction, horizontal pressure gradients caused by a variable surface height, and Coriolis force.

An intense crowding of streamlines toward the western border of the ocean is discovered to be caused by variation of the Coriolis parameter with latitude. It is suggested that this process is the main reason for the formation of the intense currents (Gulf stream and others) observed in the actual oceans.

Introduction--Perhaps the most striking feature of the general oceanic wind-driven circulation is the intense crowding of streamlines near the western borders of the oceans. The Gulf Stream, the Kuroshio, and the Agulhas Current are examples of this phenomenon. The physical reason for the westward crowding of streamlines has always been obscure. The purpose of this paper is to study the dynamics of wind-driven oceanic circulation using analytically simple systems in an attempt to discover a physical parameter capable of producing the crowding of streamlines.

The phenomenon occurs along coastlines of such varied topography that it is clear that local topographic features do not significantly control the general streamline pattern. For the sake of simplicity the present study deals with flat rectangular oceans.

The formulation of the problem--A rectangular ocean is envisaged with the origin of a cartesian coordinate system at the southwest corner (see Fig. 1). The y axis points northward; the x axis eastward The shores of the ocean are at $x = 0, \lambda$ and $y = 0,b$. The ocean is considered as a homogeneous layer of constant depth D when at rest. When currents occur, as in the real oceans, the depth differs from D everywhere by a small variable amount h. The quantity h is much smaller than D. The total depth of the water column is therefore D + h, D being everywhere constant, and h a variable yet to be determined.

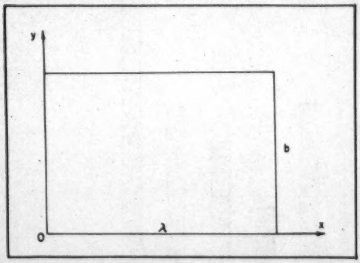

Fig. 1--Ocean basin dimensions and the coordinate system

The winds over the ocean are the Trades over the equatorial half of the rectangular basin, and Prevailing Westerlies over the poleward half. An expression for the wind stress acting upon a column of unit cross-section and depth D + h must include this dependence upon y. A simple functional form of the wind stress is taken as $-F \cos(\pi y/b)$.

In order to keep the ocean from accelerating, a frictional dissipative term is required. To keep the equations of motion as simple as possible the component frictional forces are taken as $-Ru$ and $-Rv$, where R is the coefficient of friction, and u and v are the x and y components of the velocity vector, respectively. The Coriolis parameter f is also introduced. In general it is a function of y.

The steady state equations of motion, with the inertial terms omitted because they are small, are written in the form

$$0 = f(D + h)v - F \cos(\pi y/b) - Ru - g(D + h)\partial h/\partial x \qquad (1)$$

$$0 = -f(D + h)u - Rv - g(D + h)\partial h/\partial y \quad \ldots\ldots (2)$$

To these, the equation of continuity must be added

$$\partial[(D + h)u]/\partial x + \partial[(D + h)v]/\partial y = 0 \quad \ldots\ldots (3)$$

Cross-differentiation of (1) and (2) and use of (3) results in the following equation

$$v(D + h)(\partial f/\partial y) + (F\pi/b) \sin(\pi y/b) + R(\partial v/\partial x - \partial u/\partial y) = 0 \quad \ldots\ldots (4)$$

In the actual oceans h is so much smaller than D that to a first degree of approximation (4) may be rewritten as

$$\alpha v + \gamma \sin(\pi y/b) + \partial v/\partial x - \partial u/\partial y = 0 \quad \ldots\ldots (5)$$

where the following definitions have been made

$$\alpha = (D/R)(\partial f/\partial y) \qquad \gamma = F\pi/Rb \quad \ldots\ldots (6)$$

To the same degree of approximation the equation of continuity (3) may be replaced by

$$\partial u/\partial x + \partial v/\partial y = 0 \quad \ldots\ldots (7)$$

A stream function ψ is introduced now by the following relations

$$u = \partial\psi/\partial y \qquad v = -\partial\psi/\partial x \quad \ldots\ldots (8)$$

The equation (5) is now rewritten in terms of the stream function

$$\nabla^2\psi + \alpha\partial\psi/\partial x = \gamma \sin(\pi y/b) \quad \ldots\ldots (9)$$

The remainder of this paper is simply a study of solutions of this equation. The boundary conditions upon (9) are that the shore of the ocean be a streamline

$$\psi(0,y) = \psi(\lambda,y) = \psi(x,0) = \psi(x,b) = 0 \quad \ldots\ldots (10)$$

Formal solution of the problem--If f is a linear function of y then α is a constant. Equation (9) is nonhomogeneous and therefore cannot be solved directly by separation of variables. If the right hand member is dropped, the resulting homogeneous equation is soluble by separation. Adding the solution of the homogeneous equation to a particular integral of (9) gives the general solution of (9). A particular integral of (9) is, by inspection

$$-\gamma(b/\pi)^2 \sin(\pi y/b) \quad \ldots\ldots (11)$$

The homogeneous equation is

$$\nabla^2\psi + \alpha\partial\psi/\partial x = 0 \quad \ldots\ldots (12)$$

To solve (9) by separation of variables let ψ be given in the following form

$$\psi = XY \quad \ldots\ldots (13)$$

X is a function of x only, and Y is a function of y only. Equation (9) may therefore be written as the following system

$$Y'' + n^2Y = 0 \quad \ldots\ldots (14)$$

$$X'' + \alpha X' - n^2X = 0 \quad \ldots\ldots (15)$$

The primes represent total differentiation, and n^2 is determined by the conditions (10). The general solutions of these two equations are in series form

$$Y = \Sigma(c_j \sin n_j y + d_j \cos n_j y) \quad \ldots\ldots (16)$$

$$X = \Sigma(p_j e^{A_j x} + q_j e^{B_j x}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

The constants A_j and B_j have been defined thus

$$A_j = -\alpha/2 + \sqrt{\alpha^2/4 + n_j^2}, \text{ and } B_j = -\alpha/2 - \sqrt{\alpha^2/4 + n_j^2}$$

The quantities c_j, d_j, p_j, q_j, are undetermined constants. The general solution of (9) is therefore

$$\psi = XY - \gamma(b/\pi)^2 \sin(\pi y/b) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

This solution is very general but reduces to a simple closed form when the boundary conditions (10) are imposed. First of all, the d_j and c_j vanish except c_1 corresponding to $n_1 = \pi/b$. This constant c_1 may be absorbed into p_1 and q_1. Dropping subscripts the stream function now has the form

$$\psi = \gamma(b/\pi)^2 \sin(\pi y/b)[pe^{Ax} + qe^{Bx} - 1] \quad \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

where

$$p = (1 - e^{B\lambda})/(e^{A\lambda} - e^{B\lambda}) \text{ and } q = 1 - p \quad \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

The curves (ψ = const.) are the streamlines of the ocean currents.

The velocity components u and v may be obtained from (8) by simple differentiation of the stream function

$$u = \gamma(b/\pi)^2 \cos(\pi y/b)(pe^{Ax} + qe^{Bx} - 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots (21)$$

$$v = -\gamma(b/\pi)^2 \sin(\pi y/b)(pAe^{Ax} + qBe^{Bx}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (22)$$

The value of h at any point referred to the value of h at the origin may now be obtained by integration of (1) and (2).

$$h(x,y) = -(F/gD)(e^{Ax}p/A + e^{Bx}q/B) - (b/\pi)^2(F/gD)(pAe^{Ax} + qBe^{Bx})[(\cos \pi y/b) - 1]$$
$$- \left\{(f\gamma/g)(b/\pi)^2 \sin(\pi y/b) - (\partial f/\partial y)(\gamma/g)(b/\pi)^3[\cos(\pi y/b) - 1]\right\}\left\{pe^{Ax} + qe^{Bx} - 1\right\} \quad (23)$$

Discussion of the solution for certain ocean systems--In order to clarify the meaning of the foregoing section, it is advisable to see what role the various parameters play by working some numerical examples. Three cases are discussed. All involve the same effects of wind stress, bottom friction, and horizontal pressure gradients caused by variations of surface height. The role of the Coriolis force is different in each case. First it is assumed that the Coriolis parameter vanishes everywhere, the case of the non-rotating ocean. Secondly, it is assumed that the Coriolis parameter is constant everywhere, the case of the uniformly rotating ocean. In the third case it is assumed that the Coriolis parameter is a linear function of latitude. Of the three cases, the last one most nearly approximates the state of affairs in the real ocean.

For convenience of the numerical computations the dimensions of the ocean are taken as follows

$$\lambda = 10^9 \text{ cm} = 10{,}000 \text{ km}$$
$$b = 2\pi \times 10^8 \text{ cm} = 6249 \text{ km}$$
$$D = 2 \times 10^4 \text{ cm} = 200 \text{ m}$$

The maximum wind stress F is taken to be one dyne/cm^2.

The coefficient of friction R is the only quantity for which a value must be devised. If a value of R = 0.02 is assumed, the velocities in the resulting systems approach those observed in nature.

The case of the non-rotating ocean--In this case the constants p and q are particularly simple. Within one per cent, or as closely as graphs may be drawn, p and q are given by

$$p = e^{-\pi\lambda/b} \qquad q = 1$$

The equation for the stream function is therefore

$$\psi = \gamma (b/\pi)^2 \sin (\pi y/b)[e^{(x-\lambda)\pi/b} + e^{-x\pi/b} - 1]$$

The east-west and north-south symmetry of the streamlines is immediately evident from this equation, and the actual streamlines computed from it are exhibited in Figure 2.

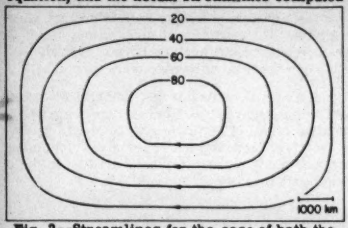

Fig. 2--Streamlines for the case of both the non-rotating and uniformly rotating oceans

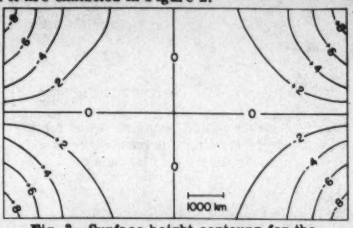

Fig. 3--Surface height contours for the non-rotating ocean in cm

The height contours are computed from (23). Since in this case there is no Coriolis force, the last two terms vanish. Height contours according to this equation are plotted in Figure 3. The general features of the non-rotating wind-driven system are a broad circulation exhibiting absolutely no tendency toward crowding of the streamlines.

The case of the uniformly rotating ocean--In the case where the Coriolis parameter is a constant 0.25×10^{-4}, the streamline diagram does not differ from that of the non-rotating basin. When the height contours are computed however from (23), a difference between the two cases becomes apparent. The third term which vanished in the first case does not vanish in this case. Height contours computed from this equation are exhibited in Figure 4. The large elevation in the central portion of the ocean provides horizontal pressure gradients that largely counterbalance the Coriolis forces. The height contours are not strictly parallel to the streamlines but nearly so.

The case where the Coriolis parameter is a linear function of latitude--In the real ocean the Coriolis force is a function of latitude. In low latitudes this function is nearly a linear one $f = y \times 10^{-13}$. The inequality in the absolute values of the quantities A and B that occurs in this case immediately makes clear the complete lack of east-west symmetry. The streamlines drawn from this formula are shown in Figure 5. The most striking feature of this figure is the intense crowding of stream-

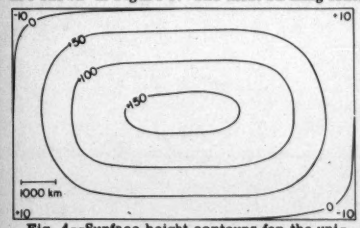

Fig. 4--Surface height contours for the uniformly rotating ocean in cm referred to an arbitrary level

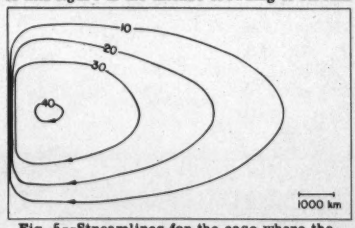

Fig. 5--Streamlines for the case where the Coriolis force is a linear function of latitude

lines toward the western border of the ocean. The rest of the streamline picture is broad and diffuse. The velocity of this system in the region corresponding to the location of the equatorial current (in the actual oceans) is about 20 cm/sec. At the western border the northward velocity amounts to as much as 240 cm/sec. The width of the region of strong northward currents is less than 100 km. The similarity that the velocity field of this simple case bears to that of the actual Gulf Stream suggests that the westward concentration of streamlines in the wind-driven oceanic circulation is a result of the variation of the Coriolis parameter with latitude.

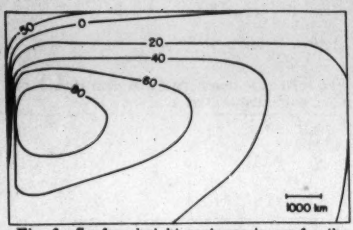

Fig. 6--Surface height contours in cm for the case where the Coriolis parameter is a linear function of latitude

The height contours computed from this case are shown in Figure 6. To extend the results of this study to the Southern Hemisphere the reader will notice that since α is unaffected by crossing the Equator and γ simply changes sign, all the diagrams may be transformed to below the Equator by simple reflection across the x axis. The crowding of streamlines is therefore toward the western border of each ocean, irrespective of hemisphere.

The artificial nature of this theoretical model should be emphasized, particularly the form of dissipative term. The writer thinks of this work as suggestive, certainly not conclusive. The many features of actual ocean structure omitted in the model should be evident.

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NOTES ON THE GEOLOGY OF IWO JIMA

Konrad B. Krauskopf

Abstract--Iwo Jima is near the south end of a chain of volcanic islands extending south from Tokyo Bay. The principal rock on the island is a soft tuff in roughly horizontal layers. Massive trachyandesite, in large part extrusive, is exposed at the north and south ends of the island. Both the lava and plutonic inclusions within the lava have a much higher alkali content than is common in the rocks of Japan proper. Suribachi-yama, the small volcano at the south end of Iwo, is made up of three roughly horizontal layers, two of tuff and one of lava, topped with a thin veneer of fairly recent pyroclastic debris. Fragments of modern coral at high elevations indicate that all or most of the island was submerged in the fairly recwnt geologic past. As the island emerged, terraces were cut in the tuff at the north end and a deposit of loose coarse sand and gravel was formed in the low central part. Numerous solfataras are the only present indication of volcanic activity. The last eruption of Suribachi probably took place several centuries ago, and there is no suggestion in the present activity that further eruptions are imminent.

Introduction

The geology of Iwo Jima has been described in considerable detail by TSUYA [see "References" at end of paper, 1936]. Since Tsuya's article is in a publication not widely known in the United States, it seems worth while to summarize a few notes on the geology of the island made during a brief visit in May 1947. Tsuya spent four days on the island and the present writer three days, neither period being long enough for a complete geological study.

The writer was sent to Iwo in response to a request by military authorities for an investigation of the possibility of an imminent volcanic eruption on the island. Apprehension had been aroused by an increase in the amount of steam from the numerous solfataras and by the appearance of two fissures several hundred feet long on the west side of the island. The writer is greatly indebted to Army authorities for an opportunity to investigate these phenomena and to study the geology of the island.

General geology

Setting--Iwo is near the south end of a chain of volcanic islands extending about 1200 km south from Tokyo Bay (see Fig. 1). Although many of the islands farther north are active volcanoes, Iwo and its neighbors owe their present shapes more to erosion acting on old volcanic material than directly to volcanic processes. Iwo has a small volcano with a deep crater at its south end (the famous Suribachi-yama), but this volcano has long been dormant.

Description of rocks--The principal rock on Iwo is a soft, yellow-brown, layered tuff (Tsuya's "Motoyama bluff tuff"). This rock makes up most of the broad north half of the island, underlying the central plateau and the terraces on all sides (see Fig. 1). The tuff is soft enough to be easily excavated, a characteristic which the Japanese used to full advantage in their desperate last-ditch defense of the north end of the island. In structure the rock varies from massive to conspicuously bedded, and in grain size from a powder with grains just visible with a hand lens to coarse volcanic breccia (fragments up to 50 cm in diameter). The coarsest breccia forms a discontinuous lowermost layer, in places separated from the finer layers above by a sharp break and in other places by a gradational contact. Bedding is fairly uniform, although individual beds gradually lens out and cross bedding on a small scale is prominent locally. No fossils were found, but the bedding and sorting suggest deposition in shallow water.

The two layers of pyroclastic material on Suribachi-yama, shown on the accompanying map as "tuff" and "pumice breccia," are probably equivalent to the upper and lower parts of the tuff at the north end of the island. On Suribachi the two varieties are mapped separately to make the structure of the volcano clearer.

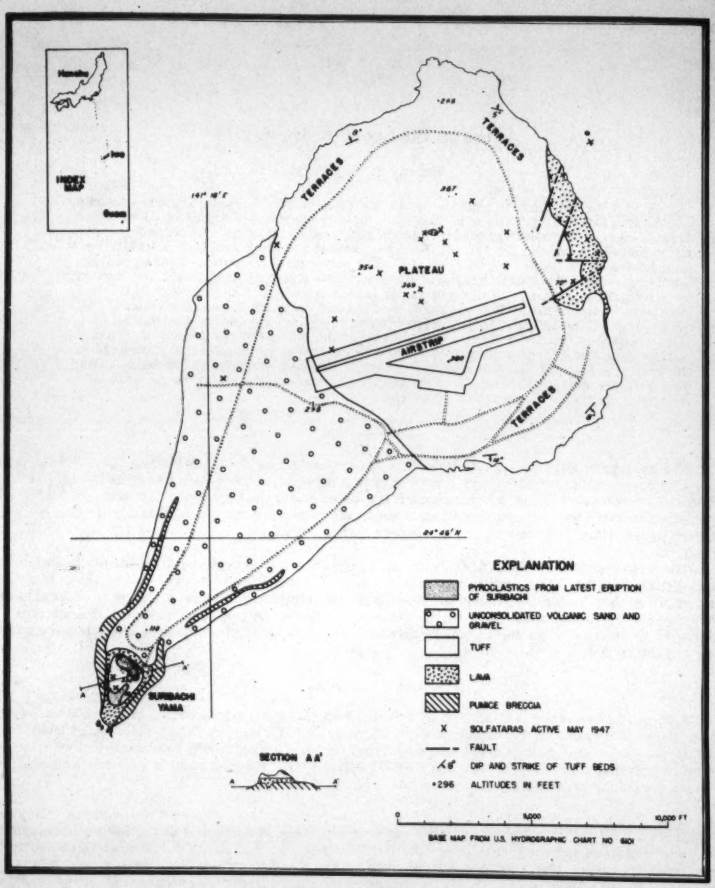

Fig. 1--Geologic sketch map of Iwo Jima

Lava is exposed on the northeast coast, in a few small outcrops on the central plateau, and between the pyroclastic layers of Suribachi-yama. The rock is medium gray, glassy to aphanitic with tiny phenocrysts, locally vesicular and locally conspicuously banded. Rough columnar jointing is prominent both on the northeast coast and on the east side of Suribachi. The petrography of the lava is described in detail by Tsuya: the rock is a trachyandesite, with phenocrysts of andesine, augite and olivine in a groundmass of alkali feldspar (anorthoclase?) and andesine. Chemical analyses tabulated by Tsuya show a high alkali content, averaging about six per cent Na_2O and four per cent K_2O.

Inclusions of coarse plutonic rock are abundant in the lava at one point on the northeast shore. This rock, also described by Tsuya, is a syenite with a chemical composition not far different from that of the lava. The high alkali content of both the plutonic and volcanic rocks is surprising in contrast with the low alkali and high calcium content of most Japanese igneous rocks, including those of the islands a few hundred kilometers north. Tsuya suggests that Iwo may belong to the central Pacific petrographic province rather than to the western Pacific province.

The other conspicuous material on Iwo is the coarse volcanic sand or gravel that occupies the isthmus between the northern plateau and Suribachi-yama. It appears in cross-bedded, water-laid deposits overlain by a veneer of dunes. The material consists of fragments mostly between one and ten mm in diameter, with very little finer sand or silt. The fragments include pumice, black glass, feldspar crystals, and a little aphanitic lava; platy feldspar crystals up to ten mm long, often twinned, are surprisingly abundant. Most of the fragments are rounded only on the corners. Steeply sloping beaches of this fine, loose gravel made the landing of Allied troops a difficult operation.

Structure--The structure of the island is simple. The beds of tuff, both at the north end and on Suribachi-yama, are flat to gently dipping. Locally on Suribachi dips up to 25° were noted, and at the north end the beds dip away from the central plateau at angles locally as much as 15°. According to Tsuya, the trachyandesite at the north end of the island is intrusive into the tuff; he cites as evidence a sea cliff showing apophyses with glassy selvages penetrating beds of tuff. This exposure was not observed by the writer, perhaps because it has been removed in recent extensive quarrying operations. Tsuya's observation demonstrates that a part of the rock is intrusive, but other evidence indicates that a part, and probably a large part, is extrusive: the lava is aphanitic to glassy, in several places shows conspicous horizontal flow structure, and has prominent but irregular columnar jointing. A basal conglomerate with pebbles and boulders of lava appears locally in the tuff just above the contact.

Faulting at steep angles is common in the tuff beds, although absence of marker beds makes it generally impossible to measure displacements. Vertical and near-vertical contacts between lava and tuff along the northeast shore seem best interpreted as fault contacts, since near the contacts flow structure remains horizontal, columnar joints remain chiefly vertical, chilling is not apparent, and apophyses do not cut the tuff. Tsuya regarded these as intrusive contacts, but his evidence seems to be an extrapolation from the one exposure of a clearly intrusive contact mentioned above. If the contacts are fault contacts, the maximum observed displacement is about 30 m.

History--The physiographic history of Iwo must include complete submergence of at least the north end, since coral fragments and rounded pebbles are common in the soil even on the highest part of the plateau. Tsuya quotes a statement by WAKIMIZU [1906] that the coral fragments are all Recent forms. Submergence of the island was followed by gradual elevation, interrupted by periods of quiescence which are recorded in well defined terraces. At least seven terraces are clearly discernible at the north end, separated by vertical distances of seven to 25 m; elsewhere the number of clearly distinguishable terraces is smaller. The expanse of loose sand and gravel over the central and southern parts of the island is probably a beach or shallow-water deposit formed when Suribachi and the northern plateau were two islands separated by a shoal. The upper surface of the deposit has been modified by wind action.

Suribachi-yama

Suribachi-yama is a steep-sided hill about 150 m high, with a large steaming crater breached on the west side. It is evidently a volcano, but a most peculiar one. The hill consists of three roughly horizontal layers, coarse pumice breccia at the base, massive lava in the middle, fine tuff on top, with a thin and discontinuous veneer of fairly recent pyroclastic material. There is no certain evidence that any one of the three layers owes its existence to the present volcanic conduit. Bedding in the upper layer does dip away from the crater (at about 25°) at one point on the east side, but elsewhere it is practically horizontal up to the crater itself; and there is no sign in these beds of a decrease in grain size away from the conduit. The lava layer is clearly extrusive, since its upper surface is blocky and vesicular, but its source is uncertain. The lower bed of pumice breccia is massive, apparently horizontal, and without conspicuous change in grain size away from the volcano. The only material clearly produced by eruptions from the present vent is the scanty debris on the upper slopes. The volcanic sand and gravel in the central part of the island may also be in part from Suribachi, but the material is hard to identify since similar fragments are found both in the Suribachi pyroclastics and in the older tuff beds.

Solfataric activity

The principal solfataras, as Tsuya points out, lie in a broad belt running ENE-WSW across the northern part of the island. In this belt are included the exposure of lava on the northeast coast and the small lava outcrops recently exposed by airfield construction on the plateau. Tsuya's assumption of a body of hot lava at shallow depths beneath this belt seems amply justified. There is no evidence of a center of volcanic activity in the northern part of the island, but both lava and tuff may have originated in a center not far from the present northeast shore.

Most of the solfataras are simply vents emitting steam and hydrogen sulfide, surrounded by areas of altered lava or tuff in which considerable sulfur is deposited. At the largest of the solfataras, near the center of the plateau, there are several boiling mudpots. Here the amount of sulfur was sufficient to make possible commercial exploitation before the War. The solfataras change their activity from time to time: Japanese records indicate the presence of large vents which are now extinct, and military personnel on the island state that a few vents have only recently appeared.

Solfataric activity is also strong in the crater of Suribachi and on the steep west slope. Steam is rising in considerable volume from a small depression in the bottom of the crater; according to military personnel the shape of the depression and the amount of steam change from time to time. Smaller vents are abundant in the walls of the crater, particularly along a NW-SE belt. Steam is rising and sulfur is being deposited along many cracks on the steep west side of the hill; sulfur deposits elsewhere on its sides show the locations of older solfataras.

Recent increase in activity

The reported recent increase in solfataric activity may be simply a minor fluctuation similar to those recorded during Japanese ownership of the island, due presumably to a change in heat supply or gas emission from the underlying lava. Another possible explanation is an increase in meteoric water: winter is the dry season on Iwo, and with an increase in rainfall during the spring more ground water may be available for volatilization.

The opening of two fissures on the west side of the island, both approximately parallel to the coast and both showing a slight displacement (maximum about 15 cm) of the west side downward, may possibly be due to minor movements of underlying bedrock. A more probable explanation, however, is a readjustment of unconsolidated material to changes in load produced by construction projects.

Neither the increase in solfataric activity nor the appearance of the fissures gives any indication that a volcanic eruption is imminent. Suribachi-yama is the only part of the island that has shown any volcanic activity in recent geologic time, and even it must have been dormant for several hundred or more probably several thousand years.

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California

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PRELIMINARY GEOCHEMICAL RESULTS AT STEAMBOAT SPRINGS, NEVADA

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Donald E. White

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Abstract--The oldest rocks near Steamboat Springs consist of metamorphosed volcanic and sedimentary rocks of unknown age intruded by granodiorite that is probably related to the Sierra Nevada batholith. The younger rocks are largely volcanic, consisting of Tertiary andesite, late Tertiary or early Pleistocene basalt and Pleistocene or possibly Recent pumiceous rhyolite. The valleys are filled with alluvium, except a small area consisting of siliceous sinter deposited by the hot springs. The springs are on the northeast edge of the Steamboat Hills, which lie in a structural trough about six miles wide. The springs appear to be structurally related to recent faults and genetically related to the magmatic source of the recent volcanic domes of pumiceous rhyolite.

Many of the springs are at or near the boiling point for this altitude; the geothermal gradient is very high, commonly exceeding one degree F per foot of depth within the explored range. Water analyses indicate a parent saline water diluted to varying degrees by water of low concentration; saline magmatic water is believed to mix with meteoric water at some unknown depth below the surface. Heavy rains have marked superficial effects on the discharge, salinity, and temperature. The discharge responds to changes in atmospheric pressure, a relationship previously found only in wells piercing artesian aquifers, but artesian conditions are either obscured or are absent.

Associated gases are principally CO_2, H_2S, nitrogen, and minor amounts of oxygen, hydrogen, and argon. High-temperature vapors also contain mercury. Cinnabar, stibnite, pyrite, and other sulfides have crystallized at depths of five to 50 feet below the surface in sinter and gravels reworked by hot water after burial under new sinter. Some siliceous muds deposited from the springs contain gold and antimony equivalent to commercial ores, and also considerable silver, mercury, copper, and arsenic. The muds are believed to precipitate largely from the thermal water at shallow depth, and rise in mechanical suspension, most abundantly during stages of high discharge; some precipitation may continue at the surface.

The acidity or alkalinity of the waters appears to be significantly related to the temperature of the springs, with the most alkaline waters tending to occur in the highest temperature springs and wells. This may be a very significant factor in the chemistry of ore-bearing solutions.

A conspicuous acid type of rock alteration is taking place near the surface at and above water level; it is believed to be largely due to sulfuric acid formed by oxidation of H_2S. Presumably a different type of alteration is taking place below water level, where rocks are in contact with near-neutral and alkaline water.

Introduction

Steamboat Springs, a group of about 50 volcanic hot springs of extraordinary importance to geologists interested in ore deposits, is located in southern Washoe County, Nevada (see Fig. 1), 12 miles south of Reno and seven miles northwest of Virginia City and the Comstock Lode. The hot springs, steam vents, several areas of hydrothermal alteration, and several deep wells drilled for hot water are on the west side of Steamboat Creek, a north-flowing tributary of the Truckee River, and are at altitudes ranging from 4550 to 5000 feet above sea level. The springs are on the northeast edge of the Steamboat Hills, a bedrock mass of about nine sq mi that lies in a structural trough between the Carson Range of the Sierra Nevada on the west, and the Virginia Range on the east. U. S. Highway 395 lies at the eastern edge of the main sinter terrace.

The semi-arid climate is strongly influenced by the Sierra Nevada. The estimated mean annual precipitation ranges from about 12 inches at Steamboat Springs to about 30 inches at the foot of the Carson Range, two miles west of the Steamboat Hills. The summers are dry except for occasional thunderstorms. Rain and snow fall frequently during the remainder of the year.

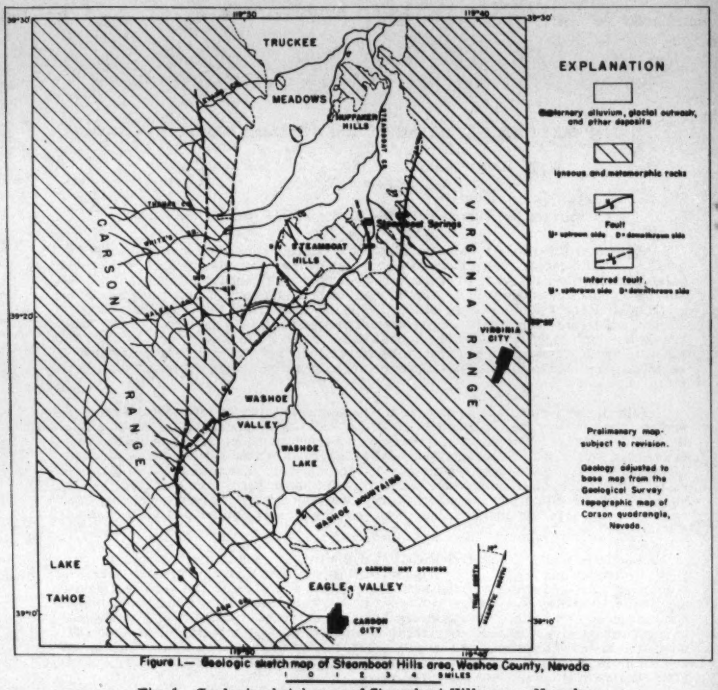

Figure 1.— Geologic sketch map of Steamboat Hills area, Washoe County, Nevada

Fig. 1--Geologic sketch map of Steamboat Hills area, Nevada

The unusual geologic conditions at Steamboat Springs, especially those which cause the deposition of sulfides of mercury and antimony by the hot springs, are known principally through the work of BECKER [see "References" at end of paper, 1888, 1889] and his assistant, LINDGREN [1903, 1913] done in the field season of 1885. This work is especially notable for laboratory experiments on the manner in which such deposits could be formed. Becker erroneously attributed the volcanic gases and heat to the basalt, and did not find the much younger domes of pumiceous rhyolite that probably came from the same magma that furnishes the gases, heat, and probably some of the water of the springs.

LECONTE [1883], in a brief but keen analysis of the geology of Steamboat Springs published in 1883, but not mentioned by Becker, described the cinnabar and sulfur and sulfates of iron and aluminum, and also the fissures of the sinter deposits, and said that veins of metallic sulfides were being deposited. He suggested that the fissures in the main sinter terrace had been opened in part by bodily sliding of the sinter toward Steamboat Creek.

LINDGREN [1903, 1913] in 1901 found minute crystals of stibnite and pyrite coating gravel in hot water at the bottom of a 30-foot prospect shaft near Steamboat Post Office. Minute acicular crystals of stibnite crystallizing from the water in one spring, and in gray siliceous mud deposited by the springs at the north end of the main terrace were described by JONES [1912, 1914], who verified the existence of metastibnite that Becker had reported finding in small quantity.

GIANELLA [1939] called attention to the nearly pure calcium carbonate deposited in wells drilled for hot water, and also to stibnite blown out by steam from wells that were being drilled in alluvium or buried sinter north of the active springs.

RUSSELL [1885] described the fault bounding the east side of the Carson Range. MEINZER [1924] discussed the origin of the springs. Important contributions have been made by several others. [LAUR, 1863; PHILLIPS, 1884, pp. 69-73, 87, 88; HAGUE and EMMONS, 1877; BAILEY and PHOENIX, 1944].

The authors began a detailed study of the geology of Steamboat Springs in May 1945. Special emphasis was put on the origin of the hot springs, and on the conditions under which stibnite, cinnabar, native mercury, pyrite, and other minerals of epithermal ore deposits are formed. This preliminary paper summarizes some of the data obtained to February 1, 1946, but does not mention all of the phases being investigated.

Geology

Steamboat Springs is a group of volcanic hot springs that issue from fissures in siliceous sinter in the northeastern part of Steamboat Hills. These low hills are in a north-trending graben-like trough about six miles wide between the bold Carson Range on the west and the Virginia Range on the east (see Fig. 1). The two ranges consist mainly of late Jurassic (?) granodiorite and older metamorphic rocks overlain by Tertiary andesites. The trough is floored by alluvium, glacial outwash and recent surficial deposits. The same group of older rocks crop out in the Steamboat Hills (see Fig. 2) except where covered by younger basalt and a dome of pumiceous rhyolite of Quaternary age. Two and possibly four other domes of rhyolite were extruded northeast of Steamboat

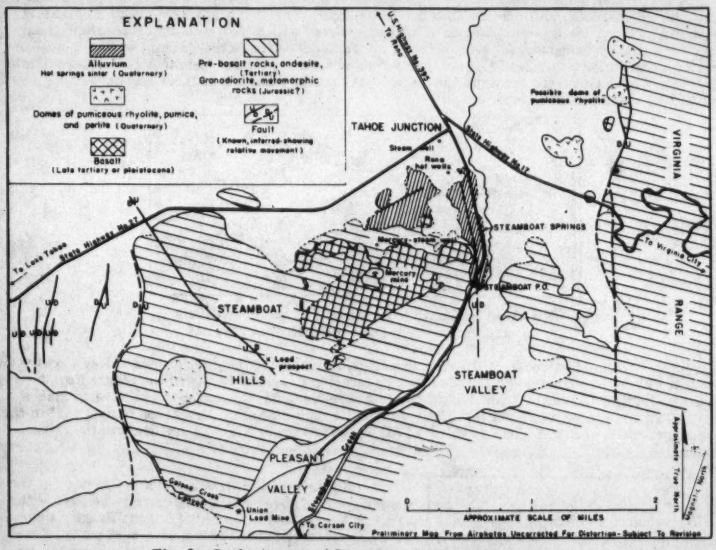

Fig. 2--Geologic map of Steamboat Springs and vicinity

Springs (see Figs. 2 to 5). The heat, volcanic gases, and probably part of the water issuing from the springs are believed to come from an igneous body at depth that is the supposed source of the rhyolite.

The geothermal gradient at Steamboat Springs is very high. Gradients of one degree F or more per foot of depth are found in wells drilled to depths as great as 200 feet to obtain hot water and steam.

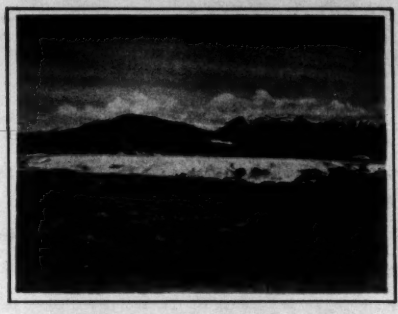

Fig. 3--View southwest of Steamboat Creek toward the main active terrace of Steamboat Springs

The thermal waters contain 2000 to 2500 ppm of mineral matter, consisting largely of Na, Cl, CO_3, HCO_3, SiO_2, SO_4, and considerable B. The springs range from slightly acid to moderately alkaline. The spring deposits consist of siliceous sinter with minor calcium carbonate, but carbonate is greatly preponderant over silica in material deposited in the thermal wells. Cinnabar, pyrite, stibnite, metastibnite (?), gold, and silver in unknown forms, and other metalliferous minerals have been deposited from the hot springs; the steam vents and effluent seepages deposit sulfur and many sulfates.

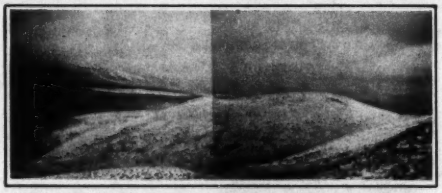

Fig. 4--View north from summit of Steamboat Hills toward the western dome of pumiceous rhyolite

Rocks--The oldest rocks of the Steamboat Springs area are metamorphosed volcanic and sedimentary rocks of unknown age intruded by late Jurassic (?) granodiorite of the Sierra Nevada batholith [JONES and GIANELLA, 1933]. Similar metamorphic rocks crop out in several places in the Virginia and Carson Ranges. The granodiorite forms most of the Carson Range, part of the Steamboat Hills, and part of the foothills of the Virginia Range, east and southeast of the Steamboat Hills.

Fig. 5--View north toward the dome of pumiceous rhyolite and perlite at the foot of the Virginia Range

Tertiary andesites form most of the surface of the western part of the Steamboat Hills, a large part of the Virginia Range, and parts of the Carson Range. Late Tertiary or early Pleistocene basalt caps parts of eastern Steamboat Hills. Tear-shaped bombs as much as three feet long lie near a vent at the southwest corner of the outcrops shown in Figure 2.

Pumiceous rhyolite of Pleistocene or possibly Recent age forms three domes in the vicinity of Steamboat Springs. Gray perlite and considerable tuff also occur in the dome at the foot of the Virginia Range (see Fig. 2).

Alluvium and slope wash of undetermined thickness cover much of the area in the valleys. In the vicinity of the hot springs and thermal areas much of the alluvium has been altered by sulfuric acid. Altered alluvium of a different type is said to occur in layers alternating with siliceous sinter in wells that were drilled to depths of as much as 200 feet in the search for hot water and steam.

Siliceous sinter consisting of opal, with considerable chalcedony and some quartz in certain areas, makes up the surface of large parts of the Steamboat Springs area. The oldest sinter is probably middle or late Pleistocene.

Geologic structure--The east side of the Carson Range is defined by large, approximately parallel normal faults dipping steeply eastward. The total displacement of the several faults is several thousand feet (see Fig. 1). RUSSELL [1885, p. 279 and pls. 3 and 4] described the frontal fault at the east foot of the Carson Range and also a recent displacement of ten to 30 feet shown by fresh scarps in earth and gravel south of Carson City near Genoa. LOUDERBACK [1923, 1924] has discussed displacements along the front of the Carson Range. The writers found several scarps in the alluvial apron of the range west of Steamboat Hills, indicating the presence of similar faults in the buried bedrock of the valley.

The Virginia Range northeast of Steamboat Springs is bounded by a large normal fault whose most recent displacement cuts alluvial fans and cones in the mouths of gulches. The relative sharpness of the cut faces of alluvium shows that the most recent movement on this fault was probably late Pleistocene or Recent. The west side of the range farther south is less sharply defined in places because bedrock surfaces slope down to Washoe, Pleasant, and Steamboat Valleys, but the frontal fault continues in this part of the range.

Apparently the bedrock of the valley is cut by north-trending faults parallel to the bounding mountain ranges, and also by northeast-trending faults that split away from the front of the Carson Range. An important fault zone here named the Steamboat Springs fault zone bounds the east side of the Steamboat Hills, and controls the principal hot springs (see Fig. 2). Northeast-trending faults play a large part in defining the Washoe Mountains 13 miles south of Steamboat Springs.

Most of the sinter deposits are elongated northward, and are broken by long sinuous fissures (see Fig. 6) that are believed to be controlled by the underlying Steamboat Springs fault zone. The

Fig. 6--Fissures in the main sinter terrace of Steamboat Springs

sinter is broken also by networks of small cracks that are probably controlled by joints in the underlying granodiorite. They are especially well shown west of the Steamboat Post Office where cracks can be traced directly through small outcrops of granodiorite that have been exposed here and there by erosion of sinter.

Cinnabar and a number of sulfate minerals are in altered granodiorite in the south wall of the open-cut of the old mercury mine (see Fig. 2), adjacent to a fumarole. They may lie on the continuation of the fault that trends northeast from the Carson Range through the mouth of Galena Creek Canyon.

The structural pattern of the area is obscured by valley fill. The valley of Steamboat Creek has been filled to considerable depth by outwash from the Carson Range. Pleasant Valley is being widened by the southeastward migration of Steamboat Creek caused by the building of an alluvial fan by Galena Creek.

Domes of pumiceous rhyolite and perlite--Three and possibly five domes of pumiceous rhyolite, perlite, and tuff were extruded in Pleistocene or possibly Recent time in the Steamboat Springs area. They are believed to have been extruded at about the same time as the youngest extrusions at Mono Craters 100 miles southeast of Steamboat Springs. The Steamboat Springs area is believed to lie above rhyolite that did not reach the surface. Mercury prospects along the frontal fault of the Virginia Range, a short distance south of the dome on the frontal fault, are believed to be genetically related to that dome.

The largest dome is in the western part of the Steamboat Hills (see Figs. 2 and 4), and consists of pumiceous rhyolite and pumice. Concentric flow-banding is exposed in a small blowout on the summit. Two other small blowouts may exist in the northeast side of the dome.

The dome on the frontal fault of the Virginia Range (see Figs. 2 and 5) contains a dike-like body of gray perlite in addition to pumiceous rhyolite, tuff, and fragmental obsidian.

The middle dome (see Fig. 2) consists of pumiceous rhyolite and pumice, which apparently froze when it reached the surface without even the mild explosive action of the other domes.

Two dome-shaped hills, one shown in Figure 2, just south of the perlitic dome, and the other a similar distance northward off the mapped area may be subsurface domes of pumice not yet stripped of their alluvial cover. The surface of each is chiefly andesitic detritus from the Virginia Range, but fragments of pumiceous rhyolite and obsidian were found. Their shapes and positions along the fault are the chief reasons for suspecting that they may be domes.

Hot springs and wells

Steamboat Springs consists of perhaps 50 active hot springs, a large number of steam vents and fumaroles, and numerous small effluent seeps. The active hot springs lie along the Steamboat Springs fault zone in an area extending about 5100 feet north from the Steamboat Post Office along the west side of Steamboat Creek (see Fig. 2). In addition, steam vents, dormant or extinct hot springs, and at least four abandoned steaming wells occur farther west in sinter and altered bedrock.

In 1945 four drilled wells that are partly cased were producing hot water and steam in commercial quantities from depths of 130 to 200 feet. Five other wells were producing small quantities of hot water and steam. About 15 or 20 old plugged wells were inactive. Such wells are drilled only deep enough to obtain a steam pressure sufficient to provide a "steam lift" for the available hot water. All of the productive wells have been drilled near the Steamboat Springs fault zone, but small quantities of steam and hot water have been obtained at other widely scattered places in the area.

The surface temperatures of most of the hot springs are between 110° F and 204° F; the latter is the approximate theoretical boiling point for pure water at that altitude. Superheated water as high as 206°.1 F has been noted at times in a few of the springs. Two small springs at the south side of Steamboat Valley have temperatures of 85° and 95° F.

Fig. 7--Steam escaping from one of the fissures on the main terrace

The geothermal gradient at Steamboat Springs is very high but the original gradient cannot be determined accurately in wells already drilled. One well 43 feet deep has a bottom temperature of 237° F, and another well 156 feet deep has a bottom temperature of 280° F. Very probably both of these wells had an original average gradient of more than one degree F per foot of depth within their explored range.

Behavior of the hot springs--The upper part of the main active terrace is broken by a system of cracks averaging about three inches wide and trending slightly west of north (see Figs. 6, 7, and 8). Many of the fissures are hundreds of feet long, most of them are sinuous, and all of them are filled in many places with detritus. Some of the fissures have been widened in places as much as six or eight feet by cracking and disintegration of the walls. In some places small cones of sinter have been deposited by the springs.

Near the highest part of the terrace the water stands at depths of about seven or ten feet below the surface and at altitudes of 4670 to 4667 feet above sea level. The largest flowing springs issue farther north from the same set of fissures, at altitudes of 4652 to 4667 feet. Relatively little water flows from springs on the east flank of the main terrace despite the presence of a secondary set of fissures striking northwest at altitudes of only 4634 to 4655 feet.

The total flow of thermal waters from the Steamboat Springs area on June 13, 1945 was estimated at about 825 gpm. This total included an estimated 500 gpm from the four producing thermal wells; about 250 gpm discharged directly into the bed of Steamboat Creek; 62 gpm from the 16 measured springs on the terraces; and an estimated 15 gpm from ten unmeasured springs. Not included in the total are several small springs and seepage areas and the water evaporated from springs, steam vents, and the surface of the sinter. The water discharged directly into the creek was revealed principally by a chloride inventory of the creek, made by S. F. Turner of the Water Resources Branch, U. S. Geological Survey, and W. W. Brannock.

Fig. 8--Hot spring No. 24 discharging stibnite-bearing siliceous mud

On June 13, 1945, the discharges from the measured springs ranged from 0.3 to 12.4 gpm. The springs with the largest flows have been measured with V-notch weirs from one to three times a week since early June 1945. Those springs that discharged less than about two gpm were measured volumetrically by filling a can of known volume and determining the filling time with a stop watch. Several of these measured springs have ceased to flow, new springs have started up, and others have begun to flow again after inactive periods.

Figure 9 shows the recorded rates of discharge from the measured springs as a group during the eight-month period from June 7, 1945 to January 30, 1946. The influence of changes in atmos-

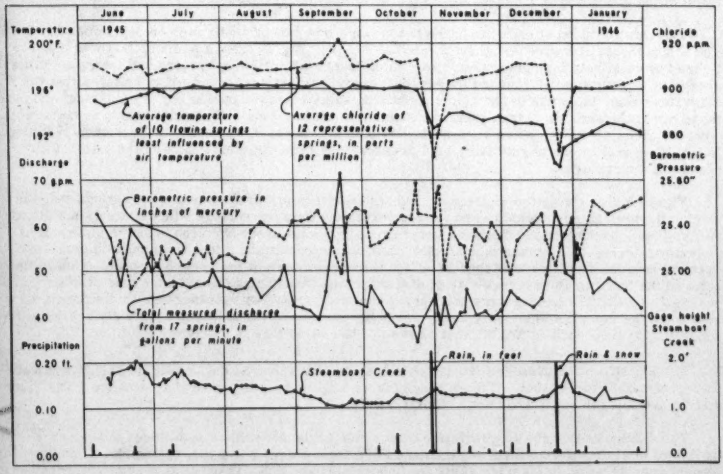

Fig. 9--Total measured discharge from flowing hot springs compared with related factors

pheric pressure on the springs is shown clearly. In general, the rate of discharge of the flowing springs increases when the atmospheric pressure falls, and vice versa. The greatest influence of barometric change is apparently shown by the nonflowing springs at the highest altitudes, where some vents show an efficiency of about 70 per cent as water barometers. This is equivalent to a change of about 0.8 foot in water level for a change of one inch of mercury in atmospheric pressure. Each spring differs in its degree of response, and a few show little or no response to such changes in pressure.

MEINZER [1928] has described the compressibility and elasticity of artesian aquifers. YOUNG [1913] described the effect of earth tides and the apparent effect of changes in atmospheric pressure on the rates of discharge of flowing artesian wells. ROBINSON [1939]; PIPER [1932]; LUGN and WENZEL, 1938; and WENZEL and SAND [1939] have described the effect of changes in atmospheric pressure on the water levels of nonflowing artesian wells. Robinson also detected the influence of earth tides.

The barometric influence at Steamboat Springs may be caused by one or more of the following factors: (1) The slight but possibly significant compressibility of water, (2) presence of gas bubbles in the water, (3) possible existence of a "steam cushion" of volcanic steam and gases, below a zone of mixture with meteoric water, and (4) the possible presence of true artesian aquifers, possessing elasticity.

Meteoric water is an important factor in the behavior of the hot springs (see Fig. 9). On November 1, following the heavy rains of October 29 to 31, the total discharge of the measured springs increased about 6.7 gpm, or 17.5 per cent more than can be accounted for by the small change in atmospheric pressure. The superficial effect of this heavy rain on the discharge of the springs ended by November 8.

The evaporation of water of effluent seepage from the sinter deposits certainly is considerable, as is shown by deposition of sulfate minerals and other salts at many places, particularly during the summer and autumn, but the total amount so evaporated per year is not known. Hot water can be found in many places at a depth of only a few inches below the surface of the sinter in the vicinity of springs, even during the summer. This effluent seepage may affect the behavior of at least some of the hot springs.

The concentration of chloride in the hot springs was exceptionally high on September 21, 1945. The atmospheric pressure fell abruptly on that day (see Fig. 9) after a summer that was characterized by relatively high pressures. The water levels in nonflowing springs and the rates of discharge of flowing springs reached the highest stages that were recorded. It is believed that the hot waters rose into parts of the sinter containing salts deposited during the dry summer, and that these minerals were then taken back into solution in the hot water. The relationship is not simple, however, because the even more abrupt fall in atmospheric pressure early in November 1945 that followed several weeks of relatively high pressure had little apparent effect on the rates of discharge of the springs.

Figure 9 also shows the arithmetric average temperature of the ten flowing springs that were least influenced by wind velocity and air temperature. Only the springs with relatively small outlets and high discharges are included in the group. It is apparent from the higher temperatures prevailing during the summer months that atmospheric conditions affect the ground temperatures in the near-surface sinter, and thereby affect the temperature of the escaping water. This is in spite of the fact that the average rate of discharge was less during the summer than at other seasons, and that the temperature of a spring commonly rises with an increase in discharge, except when the increase is directly due to rainfall. Such a relationship is particularly true of a nonboiling spring, such as No. 22, that shows marked variations in discharge (see Fig. 10).

Table 1 shows the hydrogen ion and chloride concentrations of the principal springs and wells on September 27 to 28, 1945. The pH ranged from slightly acid to moderately alkaline. The arithmetric average pH was 7.2, or very slightly alkaline.

Table 2 shows that the concentration of chloride in the hot waters in an index to the concentration of total dissolved solids. At the time the samples were collected, Spring No. 27 had the highest concentration of chloride of all the flowing springs, and was depositing abundant stibnite-bearing mud. Spring No. 16 was intermediate in chloride and No. 33 was lowest of all the principal flowing springs. The concentration in Steamboat well was even lower than that of Spring No. 33.

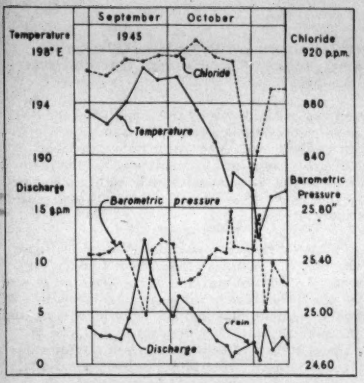

Fig. 10--Relation of discharge to temperature of hot spring No. 22, with other pertinent data

The chloride and many other components shown in these four analyses indicate only slight differences in relative concentration. This is particularly true of the more soluable compounds rarely found in hypogene ore deposits, for example, Cl, B_2O_3, and total (Na + K). An exchange between Na and K is indicated by the fact that the concentration of each varies more than the two combined. The relation of CO_3 and HCO_3 is determined primarily by the pH of the water. CO_3 is found in these waters only where the pH is greater than about 8.0.

Significantly, SO_4 varies only slightly more from a constant ratio to total solids than does Cl, B_2O_3, and total (Na + K). Sulfate therefore seems to be a constituent of the parent saline water, otherwise the relative concentration of sulfate to total solids should be highest in the most dilute waters presumably of meteoric origin. At least part of the sulfate, of course, is probably from reactions with atmospheric oxygen.

The carbonates, silica, arsenic, antimony, and calcium are the principal exceptions to the simple relationship of a constant ratio to the dissolved solids. These components are generally found in mineral veins, and their solubilities are probably influenced greatly by changes in temperature, pressure, and pH of the waters. Deviations of the amounts of silica and total carbonate from the average almost balance each other; that is, in springs such as No. 33, the silica is lower and carbonate higher, whereas the opposite is true of Nos. 16 and 27.

Table 1--Relation of hydrogen ion to temperature and chloride concentration in hot-water wells and hot springs, September 27-28, 1945

(a) pH related to temperature

Range in temperature	Number of springs or wells	Hydrogen ion concentration[a]		
		Range of pH	Average pH	
Hot-water wells, vigorously boiling	3	8.8-9.1		8.9
Springs with temperature above 198.5° F	16	7.0-8.9	7.8	7.2
Springs with temperature 198.5° F-175.5° F	16	5.3-8.0	7.1	
Springs with temperature below 175.5° F	16	6.3-8.1	6.7	

(b) pH related to concentration of chloride

Range in Cl	Number of springs or wells	Hydrogen ion concentration[b]		
		Range of pH	Average pH	
Hot-water wells with 712-956 ppm of Cl	3	8.8-9.1		8.9
Springs with 916 or more ppm of Cl	16	6.3-8.9	7.6	7.2
Springs with 872 to 916 ppm of Cl[c]	16	6.3-8.3	7.1	
Springs with 872 or less ppm of Cl	16	5.3-8.1	6.9	

[a]Determined with Beckman pH meter by E. S. Shedd. [b]Determined volumetrically by D. E. White. [c]Two springs contained 872 ppm and four springs 916 ppm of chloride; only 14 springs lie within this range. To equalize the number of springs in each major group, one "average" spring is included from each of the 872 and 916 ppm groups.

Gases

The ratio of gases (other than water vapor) to water differs greatly from spring to spring, and from time to time in individual springs. The wells probably differ likewise. Table 3 shows analyses of the gases from four representative hot springs.

All of the oxygen and at least part of the nitrogen and argon shown by these analyses are believed to be of atmospheric origin. Some air may have been introduced while the samples were being collected, but a larger amount was probably dissolved in meteoric water that mixed with magmatic water carrying CO_2, H_2S, hydrogen, and probably some nitrogen and argon. The ratio of argon to nitrogen in these samples ranged from 1:25 to 1:45.5, or considerably higher than the ratio of 1:83.3 in the atmosphere. Part of this difference may be the result of differences in solubility of argon and nitrogen in water at various temperatures.

Native mercury in the vapors--A thin coating of metallic mercury was deposited on the inner tube of the brass armor holding the thermometer when the writers made a series of temperature records in an abandoned steam well about 1500 feet north of the old mercury mine, and a mile west of the active hot spring terrace (see Figs. 2 and 11). The inner tube of the armor assembly is a brass receptacle designed to hold three self-registering maximum thermometers side by side, and it is held in the outer armor by a screw cap. The outer armor case is a brass tube 7/8 inch in diameter, with a screw cap fitted with a fine-gauge brass screen. Another screen in the bottom, and twelve 1/4-inch holes in the wall of the outer armor facilitate the attainment of thermal equilibrium between thermometers and the water.

The well is 130 feet deep and is cased to an unknown depth; it contained 20 feet of boiling water. When bare copper wire 1/16 inch in diameter was inserted in place of a thermometer in the armor assembly, and held for five minutes in the steam and gases at any points between water level and the well mouth, a thick coating of native mercury covered most of the wire. Considerably less mercury was deposited on copper wire without armor held for the same length of time in the steam and gases in the well. Almost no mercury was deposited on copper wire in the armor that was lowered rapidly through the steam and gases and held below the surface of the water. The metallic mercury was identified by the writers with a Mineralight fluorescent lamp and screen at the University of Nevada, and later by J. J. Fahey by the same means in the laboratory of the U. S. Geological Survey at Washington.

Fig. 11--Steam well near old mercury mine

Metallic mercury was deposited on the copper wire in armor as readily five feet below the well mouth as it was one foot above water level (109 feet below the well mouth). The copper wire was almost entirely coated with mercury in five minutes in each case. The small amount of mercury that was deposited on the wire lowered quickly through the gases into the water was probably deposited during its passage through the 110 feet of gases before the water was reached.

The fact that no mercury was deposited on the outside of the outer armor case, and only small amounts were deposited on the screen in the cap during the time that the copper wire inside the armor was being almost entirely coated with metallic mercury shows that a slight temperature gradient or other minor difference in environment can mean the difference between deposition or nondeposition of mercury from natural vapors at the relatively low temperature of boiling water.

The observations shown in Table 4 were made to determine the order of magnitude of the temperature gradient between the outside and inside of the thermometer armor in the mercury-steam well. The thermometer used in this test probably attained thermal equilibrium with the vigorously streaming vapors within 30 seconds when exposed directly to the vapors, but did not quite attain equilibrium in five minutes when held in its armor. The slight temperature gradient between inside and outside of the armor was probably at least part of the cause of deposition of the mercury inside the armor.

Vapors from several of the natural hot springs and steam vents were examined at night with the Mineralight and screen. Traces of mercury vapor were detected at irregular intervals of a

Table 2--Analyses of waters from Steamboat Springs, Nevada, W. W. Brannock, analyst

Ion or item	Steamboat hot well[a] 197°.2 F	Spring No. 33[b] 135°.3 F	Spring No. 16[c] 201°.2 F	Spring No. 27[d] 204°. F	Average	Max. variation from average
	ppm	ppm	ppm	ppm		
Ca	3.9	23	e	12	...	...
Mg	<1	2	e	<1	...	...
Na	605	602	666	707	...	...
K	56	54	81	75	...	...
Li	6	6	6	7	...	...
Al	<1	<1	e	<1	...	...
Fe	<0.1	<0.1	<0.1	<0.1	...	...
Ba	f	f	f	f	...	...
NH_4	<1	<1	<1	<1	...	...
CO_3	104	f	f	20	...	...
HCO_3	191	419	320	292	...	...
SO_4	105	106	131	129	...	...
Cl	747	752	897	949	...	...
F	1.8	1.6	2.0	2.2	...	...
NO_3	f	f	f	f	...	...
AsO_4	0.7	0.7	e	2.5	...	...
SbO_3	0.2	0.1	e	0.5	...	...
Se	f	f	e	f	...	...
Hg	<0.01[g]	<0.01[g]	e	<0.01[g]	...	...
B_2O_3	154	158	179	192	...	...
SiO_2	222	205	311	317	...	...
Total solids at 180° C	2047	2085	2385	2508	...	...
pH	8.6	7.7	e	8.2	...	...
	pct[h]	pct[h]	pct[h]	pct[h]	pct[h]	pct[h]
Ca	0.19	1.10	e	0.48	0.59	86.0
Na	29.5	28.9	27.9	28.1	28.6	3.1
K	2.7	2.6	3.4	3.0	2.9	17.2
(Na + K)	32.2	31.5	31.3	31.1	31.5	2.2
Li	0.29	0.29	0.25	0.28	0.28	11.0
CO_3	5.08	f	f	0.80	1.47	245.0
HCO_3	9.33	20.1	13.4	11.6	13.6	47.7
$(CO_3 + HCO_3)$	14.4	20.1	13.4	12.4	15.1	33.1
SO_4	5.12	5.08	5.48	5.14	5.20	5.4
Cl	36.5	36.1	37.6	37.8	37.0	2.4
F	0.09	0.08	0.08	0.09	0.085	5.9
AsO_4	0.03	0.03	e	0.10	0.063	59.0
SbO_3	0.01	0.005	e	0.02	0.012	67.0
B_2O_3	7.52	7.58	7.51	7.66	7.55	1.5
SiO_2	10.8	9.8	13.00	12.6	11.6	15.5

[a]Drilled March 1945; 210 feet north of Steamboat Post Office; sample collected when discharging, August 4, 1945; hottest water not accessible.

[b]Also known as Chicken Soup Spring; southernmost of the principal hot springs; 325 feet southwest of Post Office; sample collected July 30, 1945.

[c]4400 ft north of Post Office; southeast of the principal flowing springs; sample collected August 4, 1945.

[d]460 ft north-northwest of spring No. 16. Deposits black siliceous mud containing minute acicular crystals of stibnite; sample collected July 30, 1945.

[e]Not determined.

[f]Looked for, but not found.

[g]Mercury determined with fluorescent lamp and screen by J. J. Fahey in the laboratory of the U. S. Geological Survey.

[h]Per cent of total solids (180°C).

few seconds in a boiling spring (No. 17) and a steam vent (No. 39). Spring No. 17 is superheated periodically as much as one degree F, and the steam vent No. 39 contains vigorously boiling water a few feet below the surface of the sinter, with steam escaping under slight pressure.

Several other hot springs and steam vents were tested with apparent negative results, but in each of these cases either the temperature was below boiling, or the hottest vapors were not

Table 3--Analyses of gases from four representative hot springs, Steamboat Springs, Nevada (in mole per cent)[a]

Item	21[b]	24[c]	26[d]	16[e]	Limits of error
Temperature of water °F	192	204	205	202	. . .
pH of water[f]	6.9	7.7	8.3	7.2	. . .
Hydrogen	0.11	0.20	0.21	g	0.02 ±
Nitrogen	0.75	5.21	2.74	1.82	0.05 ±
Oxygen	0.11	0.10	g	0.14	0.02 ±
Hydrogen sulfide	0.38	1.06	0.45	0.77	0.04 ±
Argon	0.03	0.14	0.08	0.04	0.01 ±
Carbon dioxide	98.61	93.29	96.52	97.23	0.10 ±
Hydrocarbons[h]	g	g	g	g	. . .

[a]Samples collected June 20-26, 1945; determined with a Consolidated Mass Spectrometer on October 10, 1945 by the National Bureau of Standards.
[b]Northernmost flowing spring in summer and autumn of 1945; 5100 feet north of Steamboat Post Office.
[c]Intermittent spring in fissure 675 feet south of spring No. 21.
[d]Small geyser 3000 feet south of spring No. 24; 1400 feet north of Post Office.
[e]Perpetual spouter spring, 175 feet east of spring No. 24.
[f]Determined with a Beckman pH meter on water samples collected September 27-28, 1945.
[g]Not found.
[h]Maximum 0.03 mole per cent.

Table 4--Temperature differences between outside and inside of the brass thermometer armor, as recorded by self-registering maximum thermometer suspended in mercury-depositing steam well, Steamboat Springs, Nevada

Time interval	Temperature	
	Thermometer in armor	Thermometer without armor
min	°F	°F
1/4	201.1	202.2
1/2	201.9	202.4
1	202.1	(Thermometer broke)
2	202.2	. . . .
5	202.3	. . . .

accessible with the fluorescent lamp. The apparently negative results therefore may be the result of rapidly decreasing volatility of mercury at and just below the boiling point of water at that altitude. Native mercury was not found in the sinter around the hot springs and steam vents despite careful search, probably because the mercury escapes into the air as vapor.

Hot spring deposits

Hot springs have been depositing sinter at Steamboat Springs more or less continuously for many thousands of years, and the total volume of sinter is considerable. Only a small amount was being deposited at the surface in 1945 and 1946, principally in small areas on the large terrace west of Steamboat Creek.

Very fine grained, dark-gray to black mud was deposited from time to time in 1945 and 1946 by the hot springs of greatest discharge and highest temperature. These springs lie in an area 700 feet long centered about 4800 feet north of the Post Office (see Fig. 8). Springs Nos. 17, 21,

22, 24, 27, 28, and 34 deposited most of the mud, at least part of which was carried up from below the visual limit of a few feet depth in the springs. The mud consists of minute light-colored particles with a low index of refraction that are believed to be silica gel or opal. Angular particles of quartz, altered feldspar, and flakes of mica in the mud from several springs may have been derived from the underlying granodiorite, or possibly from contamination by wind-blown dust.

Minute acicular crystals of stibnite in individual crystals and rosette-like clusters barely identifiable with a 20x hand lens make up 0.2 to 4.0 per cent of the mud by weight. Their relative abundance apparently determines the color of the mud. Stibnite was also found floating as a thin scum on the surface of spring waters, especially in spring No. 24 (see Fig. 12).

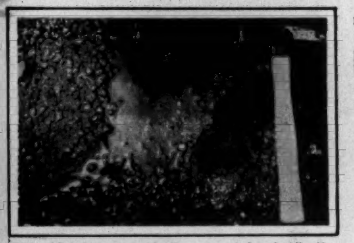

Fig. 12--Minute acicular crystals of stibnite floating on the surface of water discharged by spring No. 24 in June 1945

Pyrite was identified in the mud; cinnabar has not been recognized. Carbonates are uncommon in surface deposits, but they exceed silica in deposits formed in the producing wells, and they may be deposited also at depth in the sinters where chalcedony, quartz, opal, cinnabar, and stibnite are deposited by the hot waters.

The chemical composition of the mud is shown in Table 5.

Table 6 shows the amounts of gold, silver, mercury, antimony, and other metals in the muds deposited by three of the principal hot springs.

The concentrations of gold, silver, and antimony in these muds are of exceptional interest because they equal or approach the concentrations found in many commercial ores. The mud from spring No. 27 contains as much antimony as the mine-run of material removed from most antimony mines in the United States and Mexico. The mud from spring No. 24 contains more gold than many gold ores that are mined. Most of the iron is probably in pyrite. The mud from spring No. 24 contained 2.63 per cent Fe soluble in HCl that must have been present as iron sulfide or oxide.

In part the muds may be deposited from the hot spring waters at the surface, but they are believed to be precipitated chiefly in the water a few tens of feet below the surface, and to be carried to the surface mechanically. Much of the mud has been deposited when springs were at or near their maximum discharge rates, apparently the result of flushing action or possibly of changes in directions of movement of water at depth. Many times during June 1945 spring No. 24 was almost black from the large quantities of stibnite, pyrite (?), and silica carried up in the water. This spring deposited 5.5 cu ft of stibnite-bearing mud on the surface of the sinter terrace during one 24-hour period on May 28-29, 1945. A sample of water collected from this spring on June 1 contained 11.75 g of the mud (dry weight) per gallon.

The total amount of sinter at Steamboat Springs is large, although the amount being deposited in 1945 and 1946 was small. The first sinter deposited on the old erosion surface probably cemented pebbles and cobbles of granodiorite and other rocks, and the same type of cementing was effected at higher levels when flash floods or other agencies carried rock detritus onto the surface of the growing sinter terraces. Most of the sinter, as far as could be determined, was formed by the drying of siliceous muds and by the direct precipitation of silica from the water, probably as a result of evaporation. Both of these processes are occurring at the present time near the active springs.

For the student of ore deposits, one of the most significant features at Steamboat Springs is the large quantity of originally porous sinter that has been reworked and filled with opal, chalcedony, and some quartz by the hot waters after its burial under younger sinter. Radial clusters of acicular crystals of stibnite were found on the walls of small cavities and embedded in opal in the reworked sinter. These crystals were three to four times longer than the longest crystals that were found transported to the surface of the hot springs. Fine-grained cinnabar that blackens on exposure to the sunlight was found in many parts of the older, more eroded sinter west of the active springs.

Table 5--Spectrographic analyses of recent deposits at Steamboat Springs, Nevada[a]

Compound or Element	Carbonate deposits of the old Steamboat well[b]			Hot Spring No. 24[c]
	Sample A[d]	Sample B[e]	Sample C[f]	
SiO_2	....	....	....	>10
Al_2O_3	>10	>10	1-10	1-10
Fe_2O_3	>10	1-10	1-10	1-10
CaO	>10	>10	>10	0.X
MgO	0.X	0.X	0.0X	0.0X
TiO_2	0.X	0.X	0.0X	0.0X
MnO	0.0X	0.0X	0.0X	0.00X
Na_2O	....	....	....	0.5
ZrO_2	0.01	0.01	0.01	g
BeO	0.0002	0.0004	0.0008	0.0007
SrO	0.1	0.1	0.1	0.006
BaO	0.04	0.04	0.1	0.08
As_2O_3	g	g	0.04	0.03
Sb_2O_3	0.03	0.02	0.01	0.4
NiO	0.001	0.0002	0.0002	0.0002
V_2O_5	0.02	0.02	g	0.02
Cr_2O_3	0.008	0.004	0.002	0.002
MoO	0.005	g	g	g
Ti_2O_3	g	g	0.004	0.02
CuO	0.001	g	0.001	g
B_2O_3	0.004	0.005	0.02	0.04
Pb	0.001	0.002	0.001	0.0
Ag	g	g	0.0004	0.001
Au	g	g	g	0.001

[a]Spectrographic analyses by Esther W. Claffy and K. J. Murata, U. S. Geological Survey; the following chemical elements either are absent, or are in amounts too small to be detected: Bi, Re, Y, Yb, Ce, La, Nd, Zn, Cd, In, Ge, Sn, W, Pt, Pd, Cb, Ta, and Co.

[b]Well drilled 200 feet north of Steamboat Post Office about 1939.

[c]Hot spring No. 24 is 4425 feet north of the Post Office, and 675 feet south of spring No. 21; sample of stibnite-bearing siliceous mud collected in June 1945.

[d]Banded carbonates and sulfides deposited prior to March 1945 on the bottom of the overflow box; abundant euhedral pyrite of cubic and octahedral habit; sample probably contained sulfides and fragments of sinter and altered alluvium from the wall of the drill hole below the casing, and of travertine deposited in the well and later pulverized by redrilling to clean the well.

[e]Sample from side of same box as d, but from deposit formed below normal water level.

[f]Sample from side of same box, but from deposit formed above normal water level, and therefore subjected to wetting and drying.

[g]Not found.

Arsenopyrite, pyrite, stibnite, and some cinnabar occur in sinter and altered gravels on the dump of a shaft about 2000 feet west of the most active springs. It appears that these minerals were deposited within 40 to 50 feet of the surface.

Altered bedrock

All types of bedrock in the vicinity of the hot springs and steam vents show plainly visible evidence of alteration. Little time has yet been available, however, for this part of the study. The granodiorite of the old mercury mine (see Fig. 2) has been so changed and leached that a cubic foot of the rock can be lifted with one hand. Much of the alteration apparently results from

the attack of H_2SO_4 which is formed by the oxidation of H_2S at and near the surface. The only sulfur gas found in the gas analyses (see Table 3) is H_2S, but the odor of SO_2 can be detected in the air around some of the vents. Tests with pH papers have shown that the areas containing sulfur and sulfates are strongly acid, usually with a pH of 1 or 2. This condition was first discovered when parts of the authors' clothing disintegrated. Although spring No. 24 had a pH of 7.9 when it was most actively depositing silica and stibnite, the loose sinter around the vent and immediately above water level had a pH of less than 2.

Table 6--Metals in siliceous muds deposited by hot springs, Steamboat Springs, Nevada[a]

Item	21[b]	24[c]		27[d]
Temperature of water °F[e]	192.2	204	204.5	202.7
pH of water[f]	6.9	7.9	7.9	7.9
Date collected; 1945	Sep 28	June 13	June 21	Nov. 1
Au, oz	0.005	0.33 0.33 0.33	0.36	0.02
Ag, oz	g	1.14	1.24	g
Hg, pct	0.015	.....	0.015	0.020
Sb, pct	0.26 0.26	....	1.61 1.64	3.94 3.95
As, pct	0.007 0.007	....	0.044 0.044	0.037 0.033
Cu, pct	0.003	.....	0.065	0.052
Fe, pct	1.72 1.71	....	3.45 3.39	4.07 4.11

[a]Assays of gold and silver by William I. Smyth of the Mackay School of Mines, University of Nevada; Hg, Sb, As, Cu, and Fe determined by C. E. Arrington of the Reno analytical laboratory of the U. S. Bureau of Mines.

[b]Northernmost flowing hot spring in summer and autumn of 1945; 5100 feet north of Steamboat Post Office; sample of mud was light-gray, and slightly contaminated by wind-blown material.

[c]Intermittent spring in fissure 675 feet south of spring No. 21; sample of mud was dark gray; little or no contamination by wind-blown material.

[d]460 ft north-northwest of spring No. 16 and 265 feet south of spring No. 21; outh sample of mud was gray; slight contamination by wind-blown material.

[e]Temperature of spring at time sample of mud was collected.

[f]pH determined on water samples collected September 27-28, 1945, for springs No. 21 and No. 27; the value of 7.9 was determined by means of a pH comparator set on a water sample collected from spring No. 24 on June 4, 1945; a sample of water collected from spring No. 24 on September 27, when the spring was not flowing, was determined as pH 7.7 with a Beckman pH meter.

[g]Not determined.

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UNSTEADY FLOW IN OPEN CHANNELS

Henri J. Putman

JUNIUS MASSAU [see "References" at end of paper, 1889, p. 435] gave the principle of a method for solving the type of partial differential equations involved in unsteady flow in open channels. In a later paper [1900] he developed the application to unsteady flow, reaching interesting conclusions regarding the formation, travel, and disappearance of various phenomena; such as the moving jump, the rolling flood wave, and the bore. The application of Massau's methods in combination with modern computational procedures should facilitate the study of many problems that have so far defied satisfactory solution. Massau's original papers treat more complicated cases, but a resumé based on the special case of flow in rectangular channels will illustrate the general line of attack.

The differential equations for continuous unsteady flow in a rectangular channel are (see Fig. 1) [THOMAS, 1937, Eq. 37 and 33]

$$\partial y/\partial x + (V/g)\partial V/\partial x + (1/g)\partial V/\partial t = S_o - V^2/C^2R \quad \ldots\ldots\ldots\ldots (1)$$

$$\partial y/\partial t + y\partial V/\partial x + V\partial y/\partial x = 0 \quad \ldots\ldots (2)$$

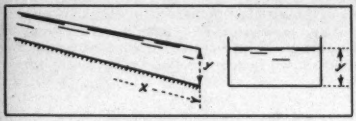

Fig. 1--Prismatic channel of Equations (1) and (2)

where g is the acceleration of gravity; x, abscissa; t, time; y, depth; V, velocity; S_o, slope of the bottom; C, Chezy coefficient; and R, hydraulic radius.

Thus, the quantities C, R, and S_o are functions of y and x and the above equations are a system of two partial differential equations with two unknown functions y and V of two independent variables x and t.

For discontinuous flow such as a moving jump, a bore, and a rolling flood wave, the principles of dynamic equilibrium and continuity also yield two equations. For rectangular channels, they are [WOODWARD and POSEY, 1941, Eq. 502 and 503]

$$V_2 = V_1 \pm \sqrt{(g/2)[(y_2-y_1)/y_1][(y_2^2 - y_1^2)/y_2]} \quad \ldots\ldots\ldots\ldots (3)$$

$$V_0 = V_1 \pm \sqrt{gy_2/2[(y_1 + y_2)/y_1]} \quad \ldots\ldots\ldots\ldots (4)$$

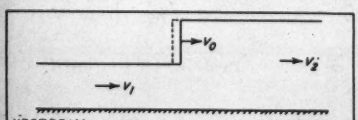

Fig. 2--Elements of flow for Equations (3) and (4)

V_0 is the velocity of the discontinuity and the subscripts 1 and 2 apply to conditions upstream and downstream, respectively (see Fig. 2).

To represent the unknown functions y and V in (1) and (2), let us take three rectangular coordinate axes, ox and ot in the horizontal plane and y along the vertical (see Fig. 3). This will yield a surface that we call the y, or depth surface, or hydraulic surface. But we can also carry V on the vertical axis and measure its value either from the same xt datum plane or from a new one. This will yield the V surface or velocity surface. The intersections of the yx and Vx planes with y and V surfaces represent the initial (t = 0) water-surface profile and its corresponding velocity curve. The intersections of the yt and Vt planes with the two surfaces represent the boundary conditions for x = 0. If we take oA on the ox axis equal to the length of the reach (portion of the length of the channel in which the water-profile history is to be obtained), the vertical planes through A, perpendicular to ox, will give with the y and V surfaces two intersections which represent the time pattern of the boundary conditions at the downstream end of the reach.

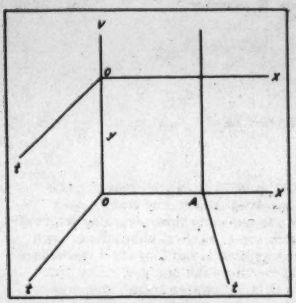

Fig. 3--Representation of functions y and V

The initial conditions are the initial surface curve and its corresponding V curve which gives the velocity of the flow at the various abscissae for the initial time t = 0.

The boundary conditions for x = 0 give the depth and velocity at the upstream end of the reach as functions of the time t. For x = oA, we have a similar interpretation.

Now if the initial curves and the boundary curves are regular curves, that is, without discontinuities in the values of y and in the values of the derivatives $\partial y/\partial x$, $\partial^2 y/\partial x^2 \ldots$, $\partial y/\partial t$, $\partial^2 y/\partial t^2 \ldots$, it may happen that the surfaces (y and V) which will join the initial and boundary conditions, are also regular, that is, without discontinuities. But we are not at all sure of it. In fact, the y and V surfaces will present jumps and other discontinuities in some particular cases, even when the initial and boundary conditions are regular.

The bore, or the rolling flood wave can appear in the middle of the surfaces, rising from zero, moving upstream and intensifying, and then declining and finally disappearing.

In steady flow, the jump occurs from high velocities to low velocities, whereas, in unsteady flow a jump may join two low velocity-surface curves. To solve a problem of unsteady flow means to find the various surface curves at successive instants. The succession of surface curves constitutes the y surface. However, we cannot find the y surface alone, as there is always an associated V surface and these two surfaces together constitute the solution of (1) and (2). In addition, whenever the initial or boundary conditions present jumps or discontinuities, or conditions which will allow these phenomena to appear, we shall need (3) and (4) in order to find the course of discontinuity.

If in (3) and (4) we let the height of the wave $y_2 - y_1$ become infinitesimal, we obtain the absolute velocity of an infinitesimal wave.

$$V_0 = V \pm \sqrt{gy}$$

The relative velocity of the infinitesimal wave with respect to the velocity of the flow is thus $\pm\sqrt{gy}$, with the positive sign applying to downstream propagation.

Characteristics of order zero are lines on the y and V surfaces having certain important properties related to the physical phenomena. Let us see what happens when the boundary curves BAC and B′ A′ C′ are formed each of two regular arcs so as to present at AA′ (see Fig. 4) discontinuities in the first derivatives. Let us see if it is possible to form an irregular solution of (1) and (2) represented by the surfaces S and S′ determined by arcs BA and B′A′ and by the surfaces T and T′ determined by arcs AC and A′C′, and the associated intersections of the surfaces S and T, and S′ and T′.

If dx, dt, dy, and dV are the differentials of x, t, y, and V at a point M, M′ of these associated curves, that is

$$(\partial y/\partial x)dx + (\partial y/\partial t)dt = dy \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$(\partial V/\partial x)dx + (\partial V/\partial t)dt = dV \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

we obtain two equations which, with (1) and (2), constitute a set of four linear equations in $\partial y/\partial x$, $\partial y/\partial t$, $\partial V/\partial x$, and $\partial V/\partial t$ considered as the unknowns.

Thus at the point MM′, if we solve (1), (2), (5), and (6) for these unknowns, since there are at least two values for each of them, they must be of the indeterminate form 0/0. Setting the numerators and the denominators equal to zero, we obtain new equations which characterize properties of points like MM′, namely, of the points which lie on the lines AM and A′M′, where the partial derivatives must have more than one value. These two lines, AM and A′M′, constitute a characteristic.

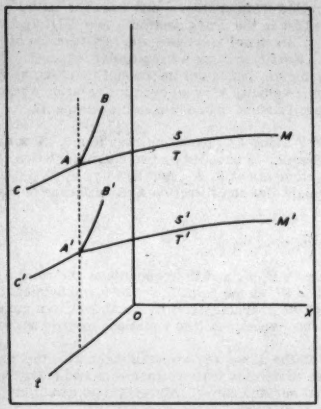

Fig. 4--Discontinuities in first derivatives of boundary curves

For a prismatic rectangular channel their equations are

$$dx = [V \pm \sqrt{gy}]dt \quad \ldots\ldots\ldots (7)$$

$$d[V/g \mp 2\sqrt{y/g}] = (S_0 - V^2/C^2R)dt \quad \ldots (8)$$

in (7) and (8). The + sign in (7) corresponds to the - sign in (8) and the - sign in (7) to the + sign in (8).

It can be shown that the characteristics have the following properties: (1) They belong to two different systems corresponding to the two choices in sign. (2) They can generate the y and V surfaces by traveling along boundary and initial curves but they do not determine those surfaces alone, by traveling one on each other. (3) By inspecting them, we notice that: If $V < \sqrt{gy}$ (small velocities), one characteristic is directed to the left, the other to the right (see Fig. 5); if $V > \sqrt{gy}$ (great velocities), both are directed to the right, as dx/dt is always positive (see Fig. 6). (4) Through any point of the surfaces pass two characteristics, one of each system, giving means to find the new surface curves when the initial surface curve is given, but in a certain domain only (see Fig. 7, Domain 1).

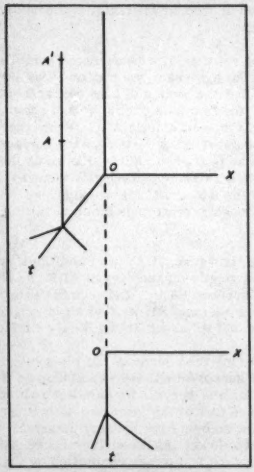

Fig. 5--Characteristics if $V < \sqrt{gy}$ (small velocities)

For small velocities, with surfaces controlled by the initial surface curve, let ABCD (see Fig. 7) be the initial surface curve projected into the horizontal plane. Given: The lines projected into ABCD of the two unknown surfaces, namely, the hydraulic surface and the velocity surface. We subdivide these lines into small and regular arcs. The element BC determines a regular integral whereupon we can imagine two characteristics BB_1 and CB_1; the triangle BB_1C can be determined by approximation. The line CB_1 is drawn in projection by replacing it by a straight line, the tangent, the equation of which is $dx = -(\sqrt{gy} - V)dt$, y and V' being the values corresponding to the point C. In a similar way the line BB_1 will be drawn by means of the equation of the characteristic of the other system $\delta x' = (V' + \sqrt{gy})$, y' and V' being the values corresponding to B.

To find V'' and y'' at B_1, we have to apply the two other equations of the characteristics (8): In the case of a prismatic rectangular channel they become, for the characteristic from downstream CB_1

$$-dy + \sqrt{y/g}\,dV = (S_0 - V^2/C^2R)\sqrt{gy}\,dt$$

or

$$-dy/\sqrt{gy} + dV/g = (S_0 - V^2/C^2R)dt \quad \ldots\ldots (9)$$

and for the characteristic from upstream, BB_1

$$y/\sqrt{gy} + \delta V/g = (S_0 - V^2/C^2R)\delta t \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

With the values of V and y being known at the points B and C, we can solve (9) and (10) for V'' and y'' by successive approximation or graphically. In the same way we determine ABA_1, then $A_1BB_1A_2$, CC_1D, $CC_1B_1B_2$, $B_1B_2A_3A_2$; finally we obtain the whole triangle AA_3D which is controlled by the initial surface curve.

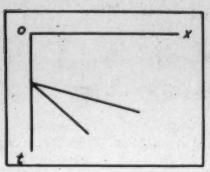

Fig. 6--Characteristics if $V > \sqrt{gy}$ (great velocities)

For surfaces controlled from upstream and from the initial surface-curve, we suppose that in the cross section A (see Fig. 7), the rate of flow, regulated by means of a sluice-gate, is a function of the time t and we have $AV = f(t)$ or, for a rectangular channel $yV = F(t)$. We might also give, instead of the rate of flow, the stage y as a function of t, or the velocity V or an equation relating y and V. We cannot, however, specify more than one condition along At.

The values of y and V along AA_3 have just been found. Now consider the triangle AA_1E which is bounded by two characteristics, A_1A and A_1E. Denoting the elements at A, A_1, and E, by y, V, y', V', and y'', V'', we find the straight line in projection A_1E by means of the equation

$$dx' = (V' - \sqrt{gy'})dt'$$

Since x', t', y', and V' are known at the point A_1, y'' and V'' at the point E can be found by means of (8) of the characteristic A_1E and the given relation at cross-section A (two equations for two unknowns).

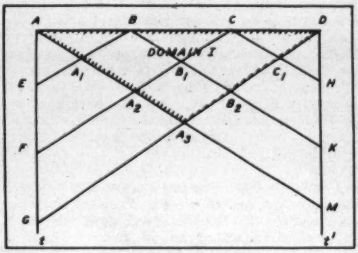

Fig. 7--Domain in which new surface curves may be found

In the same way we shall determine the surfaces controlled from downstream and from the initial surface curve. Along Dt' one condition only is allowed.

Further computation above MA_3G will yield surfaces which depend on all initial and boundary circumstances.

For great velocities, with surfaces contolled exclusively from upstream, we suppose that $V > \sqrt{gy}$, which means that the slopes of both characteristics are positive. We find (see Fig. 8) at A a characteristic AB_1 and a characteristic AA_1. From the initial surface curve AD we can find the surface ADH in which no part of the surface is controlled from downstream. We cannot specify a downstream condition along Dt'; if we give one with depths enough greater than those resulting from the upstream control to cause a moving jump will occur.

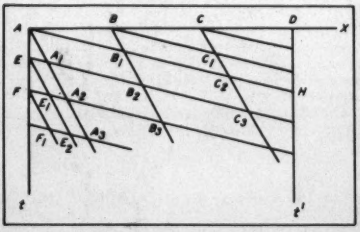

Fig. 8--Characteristics for great velocities

Upstream, however, at A, two conditions are allowed. Departing from the curves AEF, we find the hydraulic surface FAA_3. Between the two characteristics AA_3 and AH we find an intermediary y surface and its associated velocity surface.

In considering the course of the jump (see Fig. 9), let us suppose that there is a jump at B in the initial surface curve. We have the values of y and V at the foot of the jump and also at the crest. We first compute the hydraulic surface controlled by the lower initial surface curve AB, and also the hydraulic surface controlled by the higher initial surface curve BC. We know the values values of V and y at the foot of the finite wave at B. We draw BB_1, approximating a short portion of the course of the jump at B, by using the equation of its tangent $dx = V_0dt$, the value of V_0 being obtained from (4). We now draw the characteristic B_1E_1, of the higher surface (7). The elements at E_1 are known and we can compute the values of V_2 and y_2 at B_1 by writing the second equation of the characteristic E_1B_1, (8) and also (3), relating the velocities V_1 and V_2 at the foot and at the top of the jump at B_1. In this last equation, V1 and y1 are known, we have thus two equations to find V_2 and y_2 at B_1. After this we draw $E_1DD_1B_1$, then $B_1E_2D_2$, and $E_2D_1D_2B_2$ and so on.

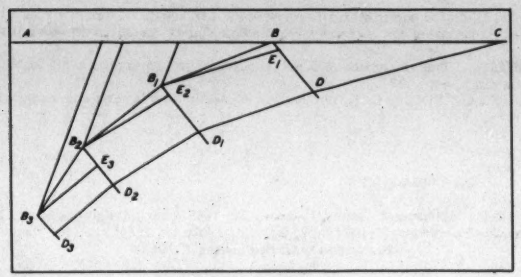

Fig. 9--Course of the jump

In determining the apparent contour of the bore, assume that the surface curve AB (see Fig. 10) is known at low tide. We can determine the surface S controlled by the initial surface curve, then the surface S′ controlled from downstream and the characteristic BC. Let us suppose that at a certain moment we find a characteristic DE which is intersected at E by the next characteristic. From DE on, the solution which consists of the two nappes controlled by EE′, FF′, and HH′ must be abandoned and we must determine the curve ER which represents the course of the finite wave which occurs. We have shown how to construct ER and S″ controlled from downstream and by the course of the jump. In this way we obtain the variation of the height of the bore and its location until it disappears.

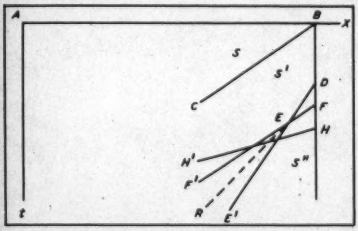

Fig. 10--Apparent contour of the bore

When two successive characteristics intersect in their projection on the x and t planes, it means that they admit an envelope in projection. This envelope is the projection of the horizontal apparent contour of the surfaces. The apparent contour in space is the locus of the points of tangency of the vertical planes tangent to the surfaces. Thus at the point where the characteristic crosses the apparent contour we have $\partial y/\partial t$ and $\partial y/\partial x$ of the form N/0. We obtain the apparent contour by expressing that the denominators equal zero. We shall have in projection the same (7) as for the characteristic without (8). The apparent contour and the characteristic are tangent in projection, but not in space.

At a point of a characteristic of the first order, the tangent planes are undetermined. However, if these tangent planes are given at an initial point A, they may be found all along the characteristic, by means of a differential equation which can be established. When the tangent plane becomes vertical, the point of tangency belongs to the apparent contour.

The upstream characteristic for a rolling flood wave can yield an apparent contour just like the downstream. If we can increase the velocity of the raise enough, there will always be a finite wave at the head of flood water.

A complete translation of Massau's work on unsteady flow is available from the Rocky Mountain Hydraulic Laboratory, Allenspark, Colorado. Thanks are due C. J. Posey and Ralph W. Powell for their help in the preparation of the present manuscript.

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A NOTE ON SOIL MOISTURE AND UNDERGROUND STORAGE

Clarence Hill Burrage

Abstract--Changes in soil moisture and the resulting underground storage-capacity are affected by many factors. Among these, the precipitation pattern, temperature, soil type, and vegetal cover are prominent. Owing to the complexity of the problem, few measurements are available. Some results of a small-scale study are offered here to add to the sum of knowledge on the subject.

It has been found that at a moderate depth, soil moisture in the latter part of the growing season is less in the forest than in the open [see "References" at end of paper, OOSTING and KRAMER, 1946]. Other data on storage in open and forest soil profiles have been reported by HURSH and HOOVER [1941]. Use of such information in a flood-control survey was reported by BURRAGE [1943]. These are only a few of the many references that treat of various portions of the problem.

As part of the watershed-management investigations being conducted by the Tennessee Valley Authority and cooperating agencies, a simply designed study was initiated near Norris, Tennessee. To determine in some degree the effect of forest cover upon soil moisture and underground storage, two stations were established. The soil is dewey silty clay loam, eroded phase, and the stations are only 100 feet apart, the one in the open being 12 feet lower. The forest station was in a 35 year old, natural, shortleaf pine stand, which had become established on an abandoned field after severe erosion. The open station was on soil very similar except more eroded, since no natural vegetation had appeared. The area was planted to shortleaf pine and black locust in 1936, but the station was in an opening with no vegetal cover, either living or dead. Gypsum blocks were buried at 6-, 12-, and 18-inch depths and soil moisture measured at irregular intervals by the Bouyoucos method [BOUYOUCOS and MICK, 1940]. Ground-water wells to a depth of four feet were installed to give a measure of soil water after field capacity was reached, since the Bouyoucos method does not operate in that range. In this region very little of the area has a well defined water table owing to the geology. The sedimentary strata are folded and much of the surface, including the site of this experiment, is underlain by limestone. Bottoms of gullies close to both stations are 20 feet below the surface and do not intersect a water table. The nearest stream is 700 feet away and approximately 75 feet lower in elevation.

During the growing season in 1945, distinct differences in soil moisture were observed at the two stations. At the six-inch depth in the open, moisture fluctuated greatly with precipitation. Most of the moisture was removed by evaporation from the bare soil surface in a short period. In the forest, moisture at this depth was alwyas greater (except immediately after rains) than in the open, and fluctuations were less pronounced. Both the litter on the forest floor and the shade of the canopy greatly reduced evaporation from the upper layer of the soil.

Relationships were reversed, however, at the 18-inch depth. Here moisture changed but little in the open, and the amount remained high throughout the growing season. But in the forest, as the growing season progressed, the soil moisture was lowered and fluctuated considerably with precipitation. This difference is caused by the transpiration draft of the vegetal cover. A portion of the record is shown in Figure 1.

The greater storage capacity of the forest soil, due mainly to larger and more numerous macroscopic openings as observed on the site, is indicated by behavior of the ground-water wells. During the period of the study, even moderate rainfall caused the appearance of water in the well in the open, but even a storm of the order of five inches in four days failed to produce water in the forest well.

These preliminary findings are in line with those of other investigators, but of course quantitative results can only be applied to areas with similar soil, vegetal cover, and climatic conditions. It is shown that there may be a considerable amount of underground storage available for flood control or consumptive use. Much research on water-soil-vegetation relationships is needed to provide a sound basis for practical watershed management. Several years ago, some

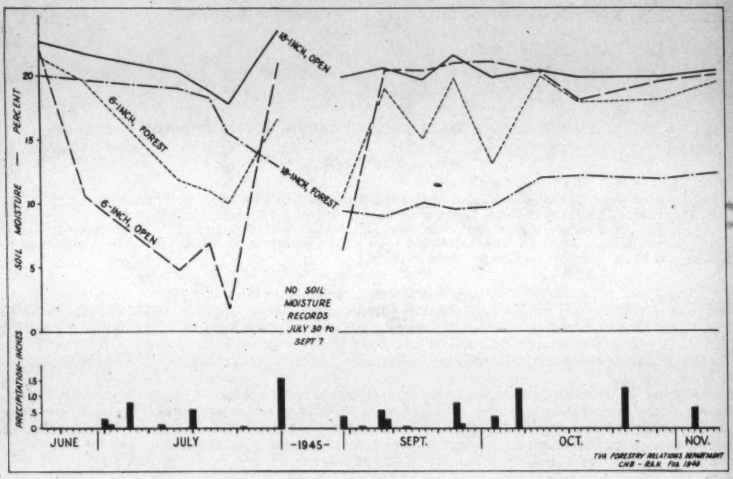

Fig. 1--Soil moisture in forest and open during parts of the growing season

aspects of this problem were pointed out by CONNAUGHTON [1939] and recently, HURSH [1946] has given a good picture of the situation, as far as foresters are concerned.

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WATER LOSS BY STREAM SURFACE EVAPORATION AND TRANSPIRATION BY RIPARIAN VEGETATION

A. R. Croft

Abstract--For the period August to October 1944, evapotranspiration losses from streamflow in Farmington Creek in northern Utah have been estimated to be about one-third of the total streamflow. Observations included streamflow, wet and dry bulb air temperatures, evaporation from several cans exposed in the stream, and water temperature. The analysis involved consideration of fluctuations in streamflow diurnally, seasonally, with changes in weather, and with the freezing of leaves. In thickly populated areas, where culinary demands for water are great, it may be economically feasible to pipe the lower reaches of water supply streams or to keep the riparian vegetation to a minimum.

Water loss from slopes and canyon bottoms--Evaporation and transpiration are recognized sources of water loss from drainage basins. This loss may be segregated into that occurring from slopes and that occurring from canyon bottoms. Water lost from slopes is largely that retained in capillary form in the soil and, therefore, not available for generation of stream flow. On the other hand, that lost in the canyon bottoms is usually due to evaporation directly from streams or to transpiration of plants that have their roots in streams or in the ground water which is adjacent to streams.

Reduction of water losses on slopes has been brought about by a drastic reduction in vegetation as shown by BATES and HENRY [see "References" at end of paper, 1928] and HOOVER [1944]. Presumably this saving occurs because less water is removed from the soil's capillary supply each year and, accordingly, less is required to raise the soil mantle to field capacity so that gravitational water can pass through the soil to generate stream flow. That the soil's capillary capacity for water must be satisfied before any appreciable snow-melt water is available to streams has been shown by CROFT and MARSTON [1943] and by CROFT [1944, 1946].

On steep watershed slopes in the Intermountain Region, where the necessity has been demonstrated for maintaining high vegetal cover to prevent soil erosion and flood-producing rainstorm runoff, reduction in cover for the purpose of increasing water yield is at variance with the need for maintaining vegetal cover for these two essential functions.

On the other hand, reduction of water losses from canyon bottoms may be attained by reducing transpiration by riparian vegetation and evaporation from the stream surface. Cutting of riparian vegetation or conveyance of water in pipes would probably reduce these losses considerably without significantly changing any of the factors that control the hydrologic characteristics of a drainage basin such as would probably result from reducing vegetation on steep slopes.

This paper is concerned only with the canyon-bottom phase of evapotranspiration loss from Farmington drainage, a 6321-acre watershed on the west face of the Wasatch Mountains between Salt Lake City and Ogden, Utah. Vegetation in the canyon bottom consists of a few fir, deciduous trees such as willow, alder, and cottonwoood, and mixed shrubs with a great variety of grasses and other herbaceous plants. Most of these plants have their roots in the stream, in the ground water adjacent to the stream or partly in the capillary fringe of the ground water table.

In this paper, the term "the stream" frequently refers to the water flowing in the channel and ground water in the canyon bottom, adjacent to and en route to the channel.

Obtaining the data--The flow of Farmington Creek was measured near its mouth at a 5000 feet elevation at a rubble masonry control section equipped with a water stage recorder. As a check on this station, numerous stage-discharge measurements were made at a second station nearby. At a point on the creek about half way up the canyon (elevation 7000 feet) evaporation from the stream surface was obtained from cans set in the creek under (a) full sunshine, (b) intermediate sunshine, and (c) full shade. Additional data were obtained on continuous air and water temperature, and on wet and dry bulb air temperature at two-hour intervals from sunup to sundown. Using creek-water

temperatures, vapor pressure of the water was obtained from vapor-pressure tables, and from the wet and dry bulb readings vapor pressure of air was calculated.

Evapotranspiration loss--The amount of water lost from the canyon bottoms by evaporation and transpiration was determined by observing (1) diurnal fluctuation of stream flow, (2) fluctuation of stream flow coincident with temporary weather changes, and (3) fluctuation of stream flow coincident with seasonal weather changes and freezing of leaves of riparian vegetation.

Diurnal fluctuation of stream flow--Diurnal fluctuation in the flow of a stream is generally thought to be caused by loss of water by evaporation and transpiration during the daytime and either the absence of loss or a slower rate of loss at night. Details of this phenomenon have been described by BLANEY, TAYLOR, and YOUNG [1930]; BLANEY, TAYLOR, YOUNG, and NICKLE [1934]; TROXELL [1933, 1936], and WICHT [1941]. There is general agreement that stream flow decreases during the hot part of the day when water is lost from the stream faster than replenishment occurs and that the flow increases when these relationships are reversed.

Evapotranspiration loss for the month of August, as indicated by diurnal fluctuation, is shown by the mean daily hydrograph for that month (see Fig. 1). This hydrograph shows a maximum discharge of 3.62 cfs at about 11^h00^m, and a minimum discharge of 2.81 cfs at about 20^h00^m. The difference between these two discharge rates, 0.81 cfs, represents the average daily water loss at the time each day when evaporation and transpiration were highest. However, the actual mean daily loss was only 0.37 cfs. This amount is the difference between the mean daily discharge of 3.25 cfs and the peak daily discharge of 3.62 cfs which probably would have been sustained had no loss occurred.

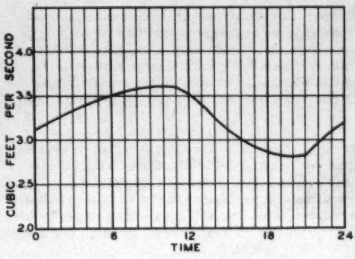

Fig. 1--Mean hydrograph, Farmington Creek, August 1944

By September 11 when stream discharge was near its lowest stage, the difference between maximum and minimum flow in the diurnal cycle had decreased from 0.81 cfs to 0.44 cfs, about half of the mean daily fluctuation during August (see Fig. 2). Mean daily discharge had decreased from 3.25 cfs to 2.57 cfs and the mean daily evapotranspiration loss indicated by diurnal fluctuation was only 0.18 cfs. This decrease in diurnal fluctuation probably reflects a decrease in the area of the stream surface and reduction of the capillary fringe area above the ground water table.

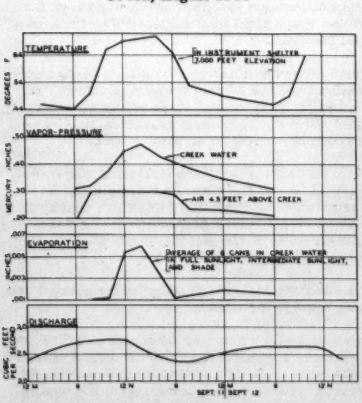

Fig. 2--Hydrograph, evaporation, and vapor pressure, Farmington drainage, September 11, 1944

It must not be assumed that peak daily discharge is the flow of the stream without evapotranspiration loss nor that minimum daily discharge is the flow with maximum loss, because evaporation from the creek occurred continually, and during August the night-time loss was about half the daytime loss (see Table 1). Then, too, transpiration to a limited extent occurs at night as well as during the day since the stomata of some plants never close. It seems clear, therefore, that maximum and minimum discharge rates in the diurnal cycle do not reflect total evapotranspiration losses.

Although the data obtained give no indication of the relative amounts of water lost by stream-surface evaporation as compared to transpiration, some relationships are indicated by temperature, vapor pressure, evaporation, and stream flow during a 36-hour period on September 11 and 12, 1944 (see Fig. 2). Peak discharge occurred and flow began a rapid decline about noon September 11. This was about five hours after sunup,

Table 1--Average evaporation from six paired cans in full sunlight, medium sunlight, and full shade, in creek water bath, elevation 7000 feet, Farmington Creek, 1944

Date	Evaporation			Date	Evaporation			Date	Evaporation		
	day-time	night-time	24 hrs.		day-time	night-time	24 hrs.		day-time	night-time	24 hrs.
Aug.	in	in	in	Sep.	in	in	in	Oct.	in	in	in
1	....	....	....	1	0.054	0.026	0.080	1	....	....	....
2	....	....	....	2	0.054	0.024	0.078	2	0.010	0.008	0.018
3	....	....	....	3	0.030	0.022	0.052	3	....	....	....
4	....	....	....	4	0.030	0.022	0.052	4	....	....	....
5	....	....	....	5	0.024	0.020	0.044	5	....	....	....
6	....	....	....	6	0.022	0.024	0.046	6	0.020	0.016	0.036
7	....	....	....	7	0.058	0.022	0.080	7	....	....	....
8	....	....	....	8	0.036	0.024	0.060	8	....	....	....
9	....	....	....	9	0.044	0.024	0.068	9	0.022	0.016	0.038
10	0.058	0.024	0.082	10	0.042	0.024	0.066	10	0.008	0.004	0.012
11	0.024	0.028	0.052	11	0.036	0.020	0.056	11	0.012	0.004	0.016
12	0.042	0.020	0.062	12	0.044	0.018	0.062	12	....	....	....
13	0.040	0.028	0.068	13	0.044	0.024	0.068	13	....	....	....
14	0.028	0.026	0.054	14	0.072	0.024	0.096	14	....	....	....
15	0.044	0.030	0.074	15	0.056	0.024	0.080	15	....	....	....
16	0.046	0.026	0.072	16	0.072	....	....	16	....	....	....
17	0.022	0.026	0.048	17	....	....	....	17	0.012	0.004	0.016
18	0.034	0.020	0.054	18	....	....	....	18	0.014	0.004	0.018
19	0.046	0.008	0.054	19	....	....	....	19	....	....	....
20	0.042	0.016	0.058	20	....	....	....	20	....	....	....
21	0.038	0.026	0.064	21	0.054	0.018	0.072	21	....	....	....
22	0.044	0.028	0.072	22	0.026	0.016	0.042	22	....	....	....
23	0.042	0.024	0.066	23	0.026	0.016	0.042	23	....	....	....
24	0.072	0.034	0.106	24	0.026	0.016	0.042	24	0.016	0.004	0.020
25	0.058	0.030	0.088	25	0.028	0.018	0.046	25	0.018	0.004	0.022
26	0.040	0.022	0.062	26	0.032	0.022	0.054	26	0.024	0.006	0.030
27	0.038	0.022	0.060	27	0.028	0.018	0.046	27	....	....	....
28	0.068	0.022	0.090	28	0.026	0.018	0.044	28	....	....	....
29	0.062	0.022	0.084	29	0.018	....	....	29	....	....	....
30	0.050	0.026	0.076	30	....	....	....	30	0.014	0.006	0.020
31	0.038	0.024	0.062					31	....	....	....
Aver.	0.044	0.024	0.068		0.039	0.021	0.060		0.015	0.007	0.022

but only two hours after evaporation from creek water began to increase rapidly. Transpiration probably was not a major factor in water loss, however, until about three hours after the stomata opened (stomata probably opened between 6^h00^m and 7^h00^m) for, if it had been, stream flow decline surely would have begun before noon on a small drainage such as Farmington. The reason for this apparent delay in transpiration may be explained by the increase in vapor pressure of the air between 6^h00^m and 8^h00^m and probable low temperature of the leaves in early morning, both of which would have a tendency to keep the rate of transpiration low for several hours after the stomata opened. It is probable, therefore, that the rate of transpiration is more closely correlated with the rate of evaporation than it is with the time of stomata opening.

Stream flow during temporary weather changes--Stream discharge increased as a result of a change from warm, dry atmospheric conditions to cool, moist conditions (see Fig. 3). Because the flow of Centerville Creek, about five miles south of Farmington Creek, changed much like that of Farmington, the Centerville hydrograph is included in Figure 3 for comparison.

The maximum discharge from Farmington Creek did not exceed 2.72 cfs during a period of fair weather from September 14 to 17, 1944. This discharge rate, after correction for storm flow from 0.16-inch of rain that fell between 6^h30^m and 11^h30^m on September, increased to 2.85 cfs and remained about at that level during two days of cooler, moister weather. Since atmospheric conditions most unfavorable for evaporation and transpiration did not occur until storm flow began, discharge even higher than 2.85 cfs probably occurred as a result of a decrease in evapotranspiration, but it was obscured by storm flow. If this inference is correct, some hydrographs intended to represent only rainstorm runoff include also some water that accrues to stream flow as a result of reduced evaporation and transpiration.

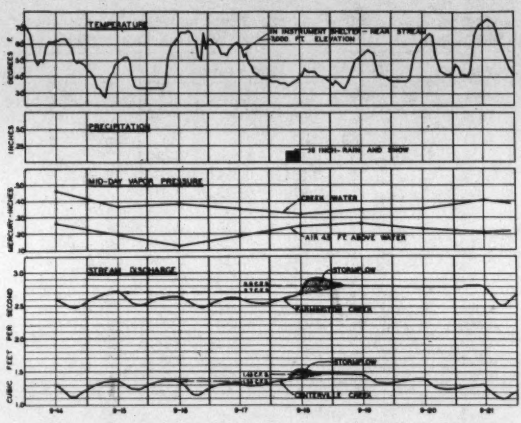

Fig. 3--Stream flow during a period of changing weather conditions

The increase in discharge that occurred during the period September 14 to 17 is closely related to an increase in the vapor pressure of air and a decrease in the vapor pressure of water during the storm period. These vapor pressure changes provided less favorable conditions for both evaporation and transpiration. Actually the average daytime vapor pressure difference for the three-day storm period was about 20 per cent less than the night-time difference during fair weather. A similar increase in the flow of Cold Water Creek, California, during a period of changing atmospheric conditions is reported by BLANEY, TAYLOR, YOUNG, and NICKLE [1934]. These flow increases of Farmington and Centerville Creeks resulted no doubt from a decrease in evaporation and transpiration because of cooler and moister weather conditions.

This increase in discharge during the period of stormy weather, over that just prior to the storm, indicates that diurnal fluctuation during fair weather is not a true measure of evapotranspiration loss from the stream.

Stream flow during seasonal weather changes--Stream flow increased from 2.4 cfs to 3.30 cfs, an increase of about 0.9 cfs, during the period September 14 to October 17 as weather conditions of late summer gradually changed to those of early fall (see Fig. 4). Since no rainfall of any consequence occurred after September 29, the increase in stream flow represents, no doubt, a corresponding decrease in evaporation and transpiration. Since a few evergreen species were still transpiring, and stream surface evaporation was still about one-third its summer time rate, the 0.9 cfs does not represent the total evapotranspiration loss for the September 14 to October 17 period.

Comparison of the magnitude of diurnal fluctuation on September 14 with the increase in flow which occurred between September 14 and October 17 as leaves were killed by frost, indicates that diurnal fluctuation was a measure of less than half of the evapotranspiration loss for the period September 14 to October 17. On September 14 the maximum loss indicated by diurnal fluctuation was 0.44 cfs and the flow increase from Septebmer 14 to October 17 was about 0.9 cfs.

The relative loss of water by stream-surface evaporation and by transpiration is shown by comparing flow increases at times when freezing temperatures killed riparian vegetation with increases related to changes in stream surface evaporation rates (see Fig. 4). Three distinct periods of low temperature, each of which included minimum daily temperatures of 30° F, or lower, occurred on September 15 and on October 3 and 17. Practically all the flow increase, which amounted to about 0.9 cfs between September 14 and October 17, occurred during these low temperature periods, apparently because transpiration was diminished by death of leaves due to frost.

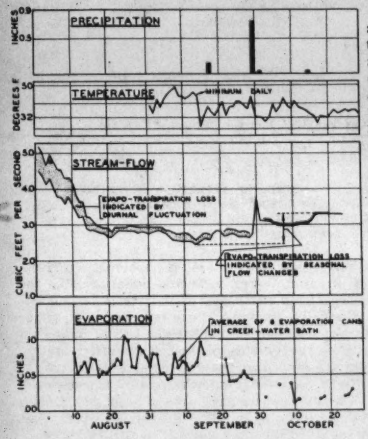

Fig. 4--Stream discharge in relation to precipitation temperature and evaporation, Farmington drainage, 1944

Although stream-surface evaporation data are only fragmentary during this same period, they show declining rates about September 15 and October 3 but the rate appears to be about constant during the time of the final flow increase about October 17. Even on this date the evaporation rate was still about one-third the mean rate for August (see Table 1). It is unlikely that a reduction of about 0.035 inch in stream-surface evaporation during the period September 15 and October 3 could greatly affect the rate of discharge. It seems reasonable therefore to ascribe the increased rate of flow largely to a decrease in transpiration rather than the decrease in evaporation.

Conclusions--The evapotranspiration loss from Farmington Creek is about one-third of the total flow during the late summer when demand for water is greatest. This amount is the loss from the combined stream courses of the drainage. Measures taken to eliminate evapotranspiration loss would of necessity be confined to the main channel and therefore only part of the loss could be eliminated. Where the demand for water for culinary purposes is great, as in the thickly populated areas along the Wasatch Mountains in Utah, it may be economically feasible to eliminate some of the evapotranspiration loss from stream channels by piping water through the lower main channels or be keeping vegetation to a minimum along the stream courses.

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EFFECT OF WATER TEMPERATURE ON FLOW OF A NATURAL STREAM

Wm. S. Eisenlohr, Jr.

Abstract--Approximately three per cent of the variation in streamflow of the Kootenai River near Copeland, Idaho, has been found to be associated with variation in water temperature. This has been determined by correlation analysis of residuals in streamflow that were not accounted for by either gage height or slope.

In rating the flow of a natural stream, the gage height is usually the most important and frequently the only independent variable used. On many streams, however, an additional variable has to be considered in order to obtain a satisfactory rating. This second variable is the slope or fall, in which changes may be produced by variations in flow or backwater. These two variables, gage height and slope, are usually presumed to define all the variations in discharge involved in any one rating. In fact, owing to limitations of the accuracy of discharge measurement and earlier methods of analysis, the effect of two variables is probably the most that could be detected. Recent refinements in the methods of analysis and greater accuracy of measuring have laid the foundation for investigating the effect of other variables such as water temperature. The present paper describes a small but apparently real effect of water temperature on the flow of Kootenai River near Copeland, Idaho. The effect is shown graphically as the solid line on Figure 1. It will be noted that the maximum effect of water temperature on the discharge over the range of observed temperatures 32° to 76° is shown to be barely three per cent, which would hardly be considered of practical significance except for precise work. It is believed, however, that there may be other streams where the effect is appreciably greater.

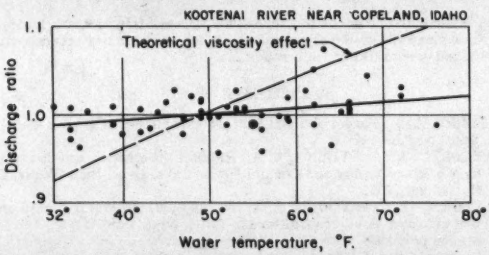

Fig. 1--Variation in discharge with water temperature

The present study was made by the author in the Division of Water Utilization, Geological Survey, under the general supervision of R. W. Davenport, Chief, and with the cooperation of T. R. Newell, District Engineer, Surface Water Division, Boise, Idaho. The measurement of water temperature was begun in 1941. Since then the results of 55 discharge measurements, not affected by ice, and for which the water temperature was observed, have been made available for analysis. They were analyzed statistically by means of multiple correlation with the results shown by the solid line in Figure 1. The variation of the plotted points from unity represents the residual deviation of the measurements from the rating not accounted for by gage height or fall, and contains all the errors of observation and effect of unknown variables as well as the effect of water temperature. In view of the dispersion of the points it was considered desirable to fit a straight line by least squares in order to eliminate the personal equation. Allowing for the loss of about eight degrees of freedom in the various relation curves used, the coefficient of correlation of 0.31 for the remaining degrees of freedom shows the correlation is significant. Hence the water temperature effect is presumably real, although small.

Kootenai River below Bonners Ferry, Idaho, is in the region of backwater from Kootenay Lake. The river is wide, deep, very sluggish for low flows, and is contained in its tortuous channel for all flows represented in this study. Kootenai River is believed to be not comparable to the much smaller channels with higher velocities investigated in Germany a number of years ago [see "References" at end of paper, SHULITS, 1933].

The fall is measured over the 34-mile reach from Klockmann Ranch to Port Hill at the Canadian boundary. Discharges are measured in the middle of the reach near Copeland and referred to the mean of the gage heights at the ends of the reach. The average area and hydraulic radius have been computed from more than 60 cross sections rather uniformly spaced throughout the reach. With that information available the criterion suggested by KEULEGAN [1938] could be used to determine whether the channel boundary was rough, smooth, or wavy in an hydraulic sense. The results of this study are given in Figure 2 where $\log(\sqrt{gRS}/\nu)$ is plotted against $V/\sqrt{gRS} - 5.75 \log R$. The line drawn, $V/\sqrt{gRS} = -19.83 + 5.75 \log (R\sqrt{gRS}/\nu)$, appears to fit the data reasonably well and indicates that the channel boundary is hydraulically wavy. Plotting the same equation as a function of the resistance coefficient, gRS/V^2, and the Reynolds number, VR/ν, and substituting a straight line averaging the curve over the range of experience, as shown in Figure 3, gives the

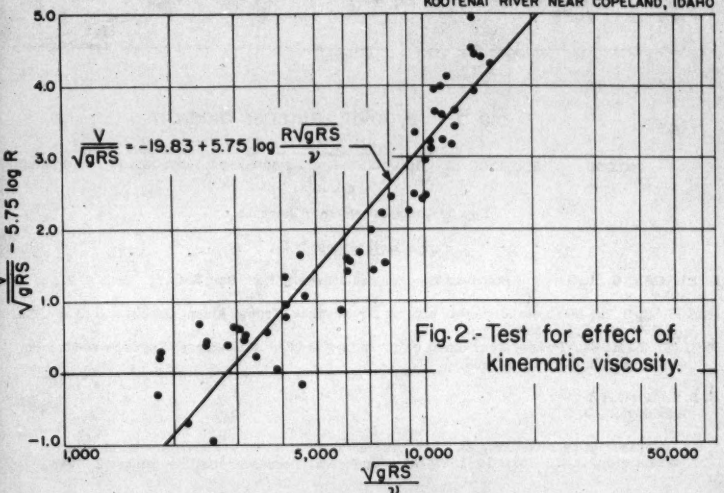

Fig. 2--Test for effect of kinematic viscosity

equation $Q = 4.08 A R^{0.88} S^{0.63} / \nu^{0.26}$. From this equation it will be seen that the discharge should vary as $\nu^{-0.26}$. This relation is shown by the dashed curve in Figure 1. Water in a natural stream is ordinarily presumed to flow with fully developed turbulence. On a river the size of Kootenai River with mean velocities as low as 0.25 ft/sec it seems logical to suppose that viscous forces could have a measurable effect on the flow, especially as the channel boundary, being of alluvial material, is relatively smooth. It might be that the only effect is to dampen the macroturbulence [MATTHES, 1947]. Examination of Figure 1 shows that the discharge does not vary with water temperature as much as the theoretical effect of viscosity would require. Several reasons for this discordance could be given: (1) There might be some other variable affecting the discharge, varying with temperature but opposite to the effect of viscosity; (2) the values of the hydraulic radius used may not represent the effective values; or, (3) for some reason, the theoretical analysis may be incorrect. Whatever the explanation it does appear that there is a real, although slight, variation in discharge of Kootenai River near Copeland, Idaho, associated with the water temperature.

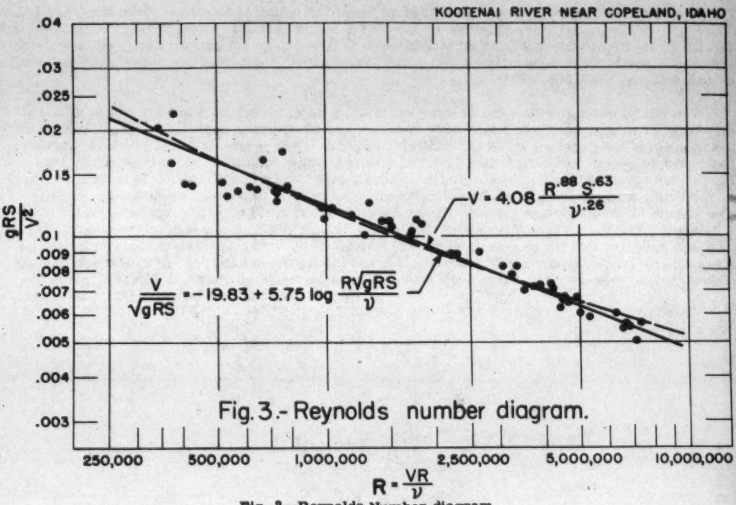

Fig. 3--Reynolds Number diagram

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NOTES ON THE DESIGN OF CURRENT METERS

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Abstract--A perfect current meter is defined and a general discussion of departures of real current meters from the ideal is presented. The Price current meter has been shown to overregister due to turbulence and angularity of the fluid stream. The propeller type of meter shows less sensitivity due to flow stream characteristics when it is properly designed. The effects on accuracy of turbulence, Reynolds Number, and meter inertia are included. Methods of rating current meters are discussed with some indication of the deficiencies of present standard procedures. The work results in a series of recommendations and design specifications for an improved propeller type of current meter.

Many theoretical and experimental investigations have been made on the hydraulic principles underlying the design and operation of current meters. Much good work of this type appears to have been neglected by some users of current meters. A review and application of the modern theories of propeller action and of turbulent flow is of value.

The perfect current meter--Use of a current meter to determine the total flow in a channel depends upon the measurement of two quantities: (1) The magnitude of the velocity; and (2) its direction relative to the selected component areas of the cross section. The total flow is

$$Q = \Sigma A_n \cdot V_n \cos \alpha_n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The area A need not be perpendicular to the axis of the stream so long as the angle α is the angle between V and the perpendicular to A. The present discussion is not concerned with the number and distribution of sub-areas, A_n, into which the cross section must be divided in order that the summation be correct, but is confined to the problems involved in determining the true value of ($V \cos \alpha$).

The perfect current meter would measure the instantaneous value of $V \cos \alpha$ averaged over the area swept by the propeller or rotating element. This result may be accomplished by a meter designed to measure either the simultaneous values of V and α independently, or the product ($V \cos \alpha$). It is not inherent in the current-meter principle that one must measure a time average of these quantities, although it is convenient to do so in practice. Meters have been constructed which indicate, and, if desired, record, the instantaneous values of either V and α or ($V \cos \alpha$).

This definition of the perfect current meter implies the following features: (1) There is no lag in response to changing velocity; a unique relationship exists between the instantaneous speed of rotation and the velocity of flow regardless of fluctuations in velocity. (2) The product ($V \cos \alpha$) is the correct average regardless of variations caused either by turbulence or by a gradient of average velocity. (3) There is no interference because of proximity of free surface or solid boundaries. (4) If the average speed of rotation over a time interval is the basis for velocity measurement, as is the usual practice, this average speed must be uniquely related to the average flow velocity regardless of the magnitude of the fluctuations in velocity about the average value. (This condition requires a linear rating curve.)

These characteristics of the perfect current meter are obvious and are stated here as the basis for a discussion of deviations in the behavior of real current meters from these ideal characteristics.

Turbulent flow--In any flow problem for which the current meter would be suitable for measuring the discharge, the flow would be "turbulent" in the technical sense that a perfect velocity instrument would record random fluctuations in magnitude and direction. These fluctuations may be very small, as in a carefully designed converging section, or they may be so large as to be readily apparent but, large or small, the essential feature of the flow is that, over an extended period of measurement, the velocity at each point has an average magnitude and direction about which the

instantaneous values vary in a random manner. If this time-average velocity itself shows a trend with time, the flow is said to be unsteady. The present discussion is concerned with steady, turbulent flow.

Quantitatively, turbulent flow can be described in terms of three mutually perpendicular velocity components: (1) V + v = instantaneous velocity in direction of time-average velocity V; (2) u = instantaneous velocity perpendicular to V; and (3) w = instantaneous velocity perpendicular to u and V.

From the definition of V, the time averages of v, u, and w are zero. The current-meter problem is to measure the time average of V regardless of the magnitude of u, v, and w. Although turbulent flow has been the subject of extensive theoretical and experimental investigations, it is not yet possible to predict the magnitude of the fluctuations in velocity for flow in any conduit or channel of specified cross section, surface roughness, and hydraulic slope. However, it is possible to formulate a qualitative description sufficiently reliable to permit an analysis of the nature of the problem of current meter design.

Imagine a perfect velocity instrument placed at the exact center of a long circular pipe of uniform roughness. A time average of the velocity components parallel to the pipe axis would yield the velocity V and the time average of u, v, and w would be zero. If this record is then analyzed in detail to determine the percentage of time that the instantaneous velocity fell in certain intervals, the u and w components would be expected to yield a symmetrical curve with negative velocities occurring as frequently as positive because of the symmetrical location of the point considered. From considerations of continuity, the v-component should also yield a symmetrical, distributive curve. Large deviations from the average velocity occur less frequently than small ones and the curve has the general form of a probability curve. Measurements show that the root-mean square value of the fluctuations in this "symmetrical" type of turbulence is usually less than 15 per cent of the average velocity.

If the fluctuating components of velocity are measured at a point which is not symmetrically located with respect to the boundaries, it is not evident a priori that the curves of instantaneous velocity versus percentage of time should be symmetrical with respect to the mean value. An example of this assymmetrical distribution would probably be found if the vertical component of velocity were measured near the bottom of a river under conditions giving rise to the frequently observed boils. High upward velocities would probably be measured during short intervals and low downward velocities during longer intervals and the distribution curve would be correspondingly skewed.

Current meters are used primarily for measurements of the flow of water in open channels in which the solid boundaries are necessarily assymmetrical with respect to any point of measurement. The highly refined techniques of aerodynamics have not been used to study turbulence in water and under such conditions but there are some studies which illustrate the general nature of the effects just discussed [see "References" at end of paper, LANE, 1940; KALINSKE, 1945; PIERCE, 1941; MURPHY, 1904]. An unusually valuable study is that of MACKENZIE [1884] from which Figures 1 and 2 have been taken. The average velocity during consecutive minutes was measured simultaneously by six recording current meters at different depths in a vertical section (see Fig. 1). In Figure 2, the number of quarter turns of the propeller in consecutive ten-sec intervals has been plotted against time. The larger pulsations in velocity usually occur near the bottom but the changes occur at about the same instant from surface to bottom. The location of these pulsations eliminates the possibility that those velocity changes are the result of wind drag on the surface and the fact that they are not uniform in magnitude from surface to bottom shows that they are not the result of surging of the river as a whole. These measurements show only the large scale components of the turbulent flow. Detailed measurements would show that these large turbulence units include, and are surrounded by smaller units of all sizes down to molecular dimensions.

The Price current meter--The facts about the nature of turbulent flow and a simple experiment, which anyone may perform, will suffice to illustrate the inherent unsuitability of the Price current meter. Fix the Price meter on its rod suspension and immerse it in still water. Oscillate the rod up and down and note the motion of the rotating element. Move the rod back and forth parallel to the tail fin. Oscillate the meter in a direction perpendicular to the tail fin. These three motions correspond to the fluctuating components of velocity u, v, and w measured about V = 0. The direction of rotation is the same for all six directions of motion. The meter does not reverse its rotation when the velocity reverses.

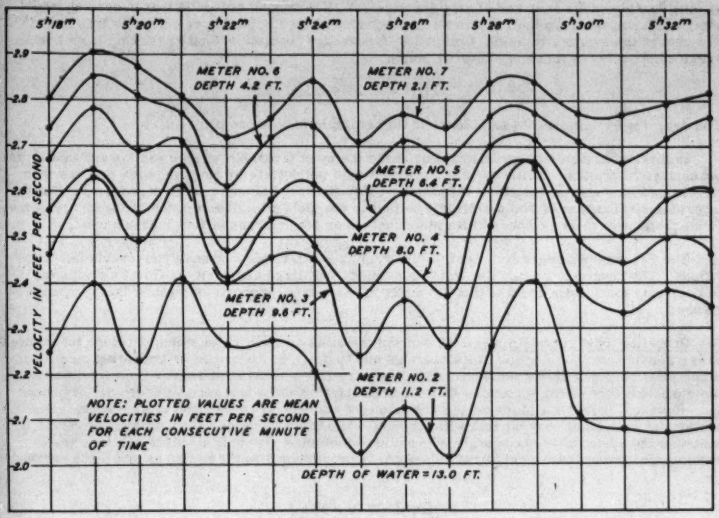

Fig. 1--Current meters in a vertical plane, curves showing pulsations for each minute, Burlington, Iowa, October 14, 1879

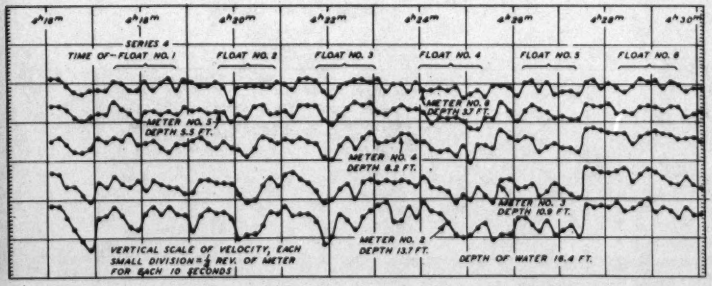

Fig. 2--Quarter turns of current-meter propeller in ten-second intervals

A second experiment, and one which has been performed many times, is to fix the Price meter so that its horizontal axis is at an angle to the motion of a towing car. The meter registers V, the velocity of the car, rather than V cos α, as requried for accurate measurement. Many other more complicated and elaborate experiments have been performed and all show this same tendency towards over-registration.

These facts about the Price meter have been cited before. It is evident that this meter is inherently inaccurate but it continues to be used for which two reasons appear to stand out. If the angle between the average flow and the meter axis is small, with the meter either fixed on a rod or hung on a suspension cable, the value of cos α is almost unity. For example, an angle

of nine degrees gives an error of only one per cent. The second reason is that in normal symmetrical turbulent flows the root-mean-square value of the fluctuating velocities is less than 15 per cent of the average velocity. Computing the average absolute velocity resulting from transverse components of this magnitude we obtain

$$\sqrt{(1)^2 + (0.15)^2} \cong 1.01$$

The over-registration due to turbulence in this example is only one per cent.

In making stream measurements, one seeks the most favorable stream section and in a large percentage of applications the direction of flow would not deviate by more than ten degrees from the channel axis and the turbulent velocities would not exceed 15 per cent of the average. These favorable circumstances would certainly be met in any field situation in which the accuracy of the Price meter was to be compared with other meters or other means of flow measurement.

The Price meter registers high but the error is small under reasonably favorable flow conditions. The danger in its use lies in the possibility that large angularity of flow or strong turbulence may exist unnoticed and that the meter itself makes no provision against this circumstance.

Propeller-type current meters--A current meter is a small motor which develops just enough power to overcome the friction in its bearings and to drive its recording or indicating mechanism. In the ideal case of a meter without inertia, the propeller would follow exactly the variations in a non-turbulent flow which is parallel to its axis of rotation and would generate zero net power output. However, unless the blade angles are properly adjusted to correspond to the radius, some sections of each blade may be acting as turbines while other sections act as brakes. Figure 3 illustrates the variation of blade angle with radius which must obtain if all blade sections are to develop zero power. The peripheral velocity U is proportional to the radius at that blade section and

$$\tan \beta = V/U = V/\omega r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

In the real propeller meter, the blades must be set at an angle with the direction β in order to develop the necessary torque. The expression for this torque is approximately

$$T = \int_{r_i}^{r_o} C_L \rho b(U^2 + V^2) r \sin \beta dr \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

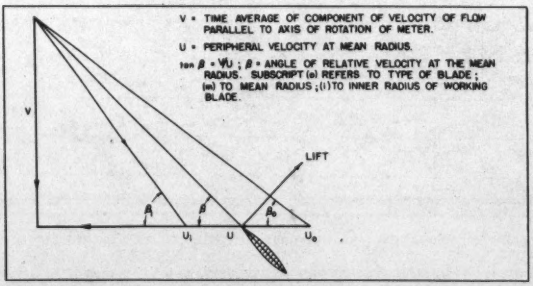
V = TIME AVERAGE OF COMPONENT OF VELOCITY OF FLOW PARALLEL TO AXIS OF ROTATION OF METER.
U = PERIPHERAL VELOCITY AT MEAN RADIUS.
tan β = V/U ; β = ANGLE OF RELATIVE VELOCITY AT THE MEAN RADIUS. SUBSCRIPT (a) REFERS TO TYPE OF BLADE ; (m) TO MEAN RADIUS ; (i) TO INNER RADIUS OF WORKING BLADE.
V
LIFT
β1
β
βo
U1
U
Uo

Fig. 3--Velocity diagram for blade section of propeller type current meter

Here, T is the torque, C_L the coefficient of lift, ρ the density of the fluid, and b the chord length of the blade at radius r. The coefficient of lift depends upon the angle of attack, α, which is the angle between the direction of the relative flow β and the position of zero lift for the blade section selected. If the angle α is small, as it should be for a current meter, C_L is a linear function of α. In a non-turbulent flow, a frictionless meter would rotate at a speed proportional to the flow velocity.

If the power required to drive a meter is specified, modern propeller theory would permit designing a suitable runner to yield desired response characteristics in a non-turbulent flow parallel to the axis of rotation. This theory has been developed for the design of ship and airplane propellers and need not be elaborated upon here. The problem here is to analyze the behavior of a propeller current meter so designed under the action of turbulent flow and flow at an angle with the axis of rotation.

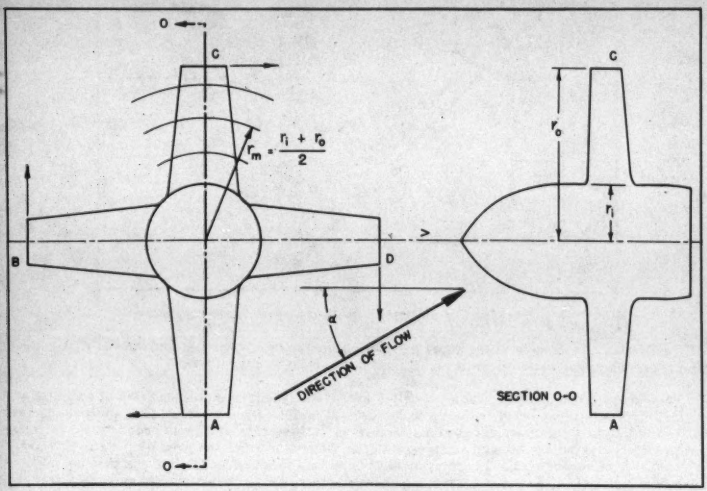

Fig. 4--Schematic drawing of propeller of a four-bladed current meter with mean velocity inclined at an angle

Figure 4 shows schematically the propeller of a four-bladed current meter with the mean flow inclined at an angle α with the axis in a plane through the axis of rotation and the blades A and C. It is evident that the flow conditions about each of the four blades are different and that each blade experiences a varying relative flow angle and velocity as it rotates. When the blades are in positions B and D, the forces can be analyzed by the usual propeller theory but in all other positions, such as A and C, there is a radial component of velocity which considerably complicates analysis. The situation is the same as that of an airplane propeller in yaw.

Figure 5 shows the flow conditions about blades B and D of Figure 4 where U_+ corresponds to blade D and U_- to blade B. The angle of attack is altered giving

$$\tan(\gamma+) = (U+)\sin\beta/[\sqrt{U^2 + V^2} + (U+)\cos\beta] \quad \ldots\ldots\ldots\ldots\ldots \text{(3a)}$$

$$\tan(\gamma-) = (U-)\sin\beta/[\sqrt{U^2 + V^2} - (U-)\sin\beta] \quad \ldots\ldots\ldots\ldots\ldots \text{(3b)}$$

Neglecting the effect of the other blades, it is evident that, if the meter is to rotate at a velocity determined by V, the velocity component parallel to the axis, the resisting torque on blade D due to the angularity of the flow must be exactly balanced by an added driving torque on blade B. Without presenting the steps in the analysis, this situation leads to the following conclusions: (1) The cross section of the blade should be symmetrical about its chord because blades B and D will interchange positions during rotation. (2) The blades should work at angles of attack which are in the region in which the lift coefficient will be a linear function of the angle of attack. (3) The transverse velocities must be small in comparison with V, so that $(\gamma+) \cong (\gamma-)$, and the angle β should be large. (4) For any given angularity of flow, the increment of resisting torque (U + in

Figure 5) exceeds the increment of driving torque on the opposite blade and the meter will under-register at large values of α. (5) Because of (3), the length of the blade ($r_1 - r_0$) should be small so that the entire blade length works at as near the most favorable value of β.

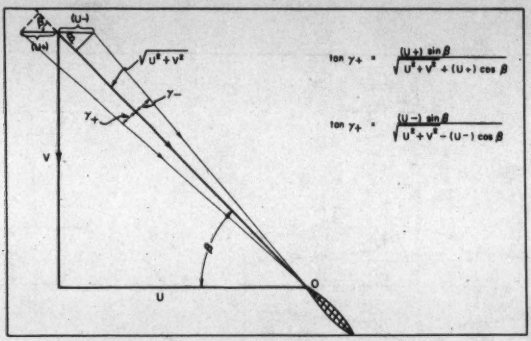

Fig. 5--Effect of angularity on flow around blade sections

Qualitative conclusions of the same general character follow from a study of the flow conditions around blades in positions A and C, and in intermediate positions.

The general conclusion is that a propeller meter will under-register in flows at an angle with its axis of rotation; that is, the velocity recorded will be less than V cos α. One approach to this problem is to use some means of guiding the flow so that the rate of flow is proportional to cos α. This principle has been used with success in some meters in which the propeller blade tips are surrounded by a shroud ring. One such meter tested by Lindquist followed V cos α to an angle of more than 30 degrees. Another possible approach is to use a large hub with blunt nose and short blades of long chord.

Effect of turbulence--The linear scale of turbulence or the linear dimensions of the fluid masses making up the turbulent flow, has an important effect on meter characteristics. If the predominant units are very large as compared with the diameter of the meter, the entire meter would be subjected to velocities having substantially the same magnitude and direction and the meter would record a series of pulsations, as in the measurements of MACKENZIE [1884]. At the other extreme, the units of the turbulence might be small as compared with the chord length of the blades and the effect of the small variations in velocity might almost cancel out and permit the propeller to rotate at a constant velocity. In any real flow, the turbulence units probably range from a maximum size dependent upon the dimensions of the channel down to very small dimensions. Because a meter must be small in comparison with the dimensions of the channel in which it is to be used, meters are probably subjected to turbulence units ranging in size from some much larger than the meter diameter down to those small in comparison with the chord of the blades. What then is the effect of turbulence on meter characteristics?

Considering a turbulent flow in which the average velocity V is parallel to the axis of rotation and the fluctuation of velocity occur in this direction only, the desirable situation is that the meter rotate at a speed proportional to the instantaneous average velocity (volume per second divided by the area) through the area swept by the blades regardless of how much the velocity at individual points in the area may deviate from the average. Equation (3), however, states that the torque, which determines the speed of rotation, depends upon the square of the velocity. Consequently the speed of rotation will depend upon the average of the squares of the velocities at points in the area and, at the same true average velocity, the speed of rotation should be greater than the instantaneous deviations of velocity from the average. Thus, fluctuations parallel to the propeller axis tend to produce over-registration.

In addition to the longitudinal fluctuations in velocity just considered, there are transverse components which alter both the angle and the magnitude of the velocity as shown in Figure 5.

Here, the turbulence has two opposing effects, namely: (1) The velocity-squared effect tends to make the meter over-register. (2) The angularity, for reasons previously discussed, tends to make the meter under-register (register less than instantaneous velocity times cos α).

Whether these two effects cancel cannot be determined exactly, except by calibration in turbulent flow.

The effects of angularity of flow and turbulence on the registration of current meters have been studied experimentally by a number of investigators [LINDQUIST, 1927; YARNELL and NAGLER, 1931; PIERCE, 1941]. The results of these investigations are in general agreement with the conclusions which follow from propeller theory and the nature of turbulent flow.

Effect of Reynolds Number--Just as the flow in a pipe or open channel breaks over into turbulent flow above a critical value of the Reynolds Number, so the laminar boundary layer on the surface of the blades of a propeller-type current meter changes over to turbulent flow at a critical Reynolds Number which varies with the turbulence of the incident flow. This point is important in connection with the rating obtained by towing through still water. The familiar break in the rating curve thus obtained is probably the result of transition from laminar to turbulent flow and would occur at a lower velocity were the rating obtained in turbulent water.

Effect of inertia--If the flow velocity varies, the current meter will lag the velocity by an amount which depends upon the rate of change of velocity and the inertia of the rotating system, including the virtual mass of the propeller. The virtual mass of the propeller is, in effect, the mass of water which partakes in the propeller motion and is small for streamlined shapes but relatively large for blunt forms such as the cups of a Price meter. The response of a meter to a change in torque is

$$\Delta T = I\, d\omega/dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

If the meter is to respond rapidly, the torque developed by a small change in flow velocity should be large, a result obtainable with a large blade area, and the moment of inertia should be small. Because the friction in the bearings depends upon the net weight or the buoyancy, it seems desirable to make the average specific gravity of the runner equal that of water but to minimize the moment of inertia by putting as much of the mass as possible near the axis of rotation.

Rating current meters--The standard method of rating current meters consists simply in towing the meter through still water at various constant velocities and counting the number of revolutions of the meter in a measured interval of time. This procedure fails to take into account the effects of angularity and turbulence but the results are presented in such form as to give the impression that a high degree of accuracy is obtainable in the field. The results are reproducible and do accurately represent the measurements obtained during calibration but turbulence and angularity of flow will introduce some error when the meter is used to measure flowing water. It would then appear that studies of current-meter characteristics, and possibly all current-meter ratings, should be made in flowing water. There are two feasible methods of rating. LINDQUIST [1924] set up a steady flow in an open channel and towed the meter both with and against the current at speeds up to 16 ft/sec. Lindquist found the effect of turbulence to be small but definitely measurable. The second method is to make the rating in a water tunnel, essentially the same in flow characteristics as a wind tunnel, and to control the degree of turbulence by "egg crates" and screens upstream. In both of these methods, the effect of angularity should be studied by setting the meter axis at different angles with the directions of the average flow.

Conclusions--The amount spent annually on water measurements and the value of the water measured make it desirable that the instruments used be inherently reliable and accurate to the point that errors in measurement are caused by the circumstances of field measurement and not by the characteristics of the meters themselves. The Price current meter suffers from the disadvantage that it does not measure the component of velocity parallel to its axis (V cos α) and generally tends to over-register as a result of a deviation from ideal flow conditions, whether resulting from turbulence or angularity of flow. The propeller-type of meter, on the other hand, registers approximately the component of velocity parallel to its axis and has tendencies towards both over-registration and under-registration which might be taken advantage of by a combination of analysis and experiment to obtain a meter responding accurately to turbulent flows at large angles with its axis. As a guide for such further development of propeller-type meters as is warranted, the authors offer the following suggestions based on this analysis and on their previous experience in the design of propeller pumps: (1) Construct the blades of symmetrical circular-arc sections so that the coefficient of lift is the same at negative and positive angles of attack.

(2) Set the blades at consistent angles (angle β in Figure 3) so that the theoretical hydraulic pitch is the same at all radii. (3) Vary the chord of the blade section so that most of the torque is developed between the hub and the mean radius. (4) Use a large hub-diameter in proportion to tip diameter to limit the variation in β. (5) Experiment with the shape of the leading edge of the hub, varying it from sharp-pointed to spherical, to discover the shape which best compensates for under-registration in flows at an angle with the meter axis. (6) Make the specific gravity of the propeller equal to that of water and place any disposable weight near the axis. (The meter should of course be balanced statically and dynamically.) (7) Calibrate each design in turbulent flow over a wide range of flow angles, α.

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HYDROLOGY OF LIMESTONE TERRANE IN SCHOHARIE COUNTY, NEW YORK

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During the summer of 1946 the writer studied the ground-water resources of Schoharie County, New York, as a part of the program of ground-water investigation being carried on in cooperation between the United States Geological Survey and the New York State Water Power and Control Commission. Because the outcrop belt of Devonian and Upper Silurian carbonate rocks is wider in Schoharie County than in other parts of the State, the effects of solution on these formations is better displayed here than elsewhere. The conditions described below probably apply on a smaller scale to the areas to the west, where the upper formations are cut out by an unconformity, and to the east in the Helderberg area, where similar effects have been described by GOLDRING [see "References" at end of paper, 1935]. However, it is probable that solution in the limestones in the Hudson Valley is not comparable because of the folded condition of the rocks.

Schoharie County is located in east-central New York. Carbonate rocks consisting of massive limestones, shaly limestones, and dolomitic limestones occur in the northern half of the County (see Fig. 1), where they underlie dissected plateaus and terraces intermediate in elevation between the

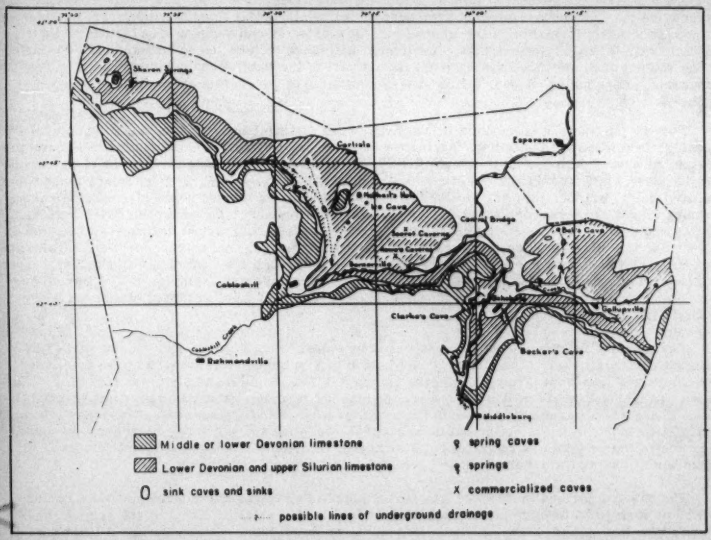

Fig. 1--Northern half of Schoharie County, New York, showing areas underlain by limestone

high plateau of Middle Devonian siltstone of the Hamilton group to the south and the lower surface on the Middle Ordovician shales and sandstones of the Schenectady formation in the Mohawk Valley to the north.

The structure of the County is simple, the beds dipping south between 100 and 180 feet to the mile. Faults are few and of small displacement. The massive limestones are cut by three sets of joints, which have average strikes of N 58° W, N 23° W, and N 50° E. Water in these rocks moves down dip along the bedding planes and along these joints, and mots of the caves in the area are controlled by these structural features.

Hydrologically the carbonate rocks in Schoharie County may be divided into two groups, the most important of which includes the dolomitic Cobleskill limestone, Rondout limestone, and Manlius limestone, of Upper Silurian age; and the Coeymans limestone, shaly New Scotland limestone, and Becraft limestone, of Lower Devonian age. The second and less important group consists solely of the Onondaga limestone of Lower or Middle Devonian age, which is separated from the lower formations by the insoluble and relatively impermeable Esopus siltstone and Carlisle Center shale. The Onondaga is 100 feet thick but does not underlie areas as large as do the lower limestones. GOLDRING [1935, p. 143] has described solution and underground drainage in the Onondaga in the Berne quadrangle at Thompson's Lake, but no sinkholes and only one cave have been observed in this formation in Schoharie County, although outcrops commonly show joints widened by solution.

The Upper Silurian and Lower Devonian limestones have a total thickness between 300 and 350 feet, and underlie broad areas between Carlisle and the village of Howes Cave, and between the county line and Gallupville, including Barton's Hill. These formations consist of six to 12 feet of dolomitic limestone (Cobleskill) at the base, 60 to 100 feet of shaly limestone (Rondout), 100 feet of massive, well-jointed limestone (Manlius and Coeymans), 115 to 135 feet of shaly limestone (New Scotland), and 15 to 30 feet of massive limestone (Becraft). That these rocks act as a unit in spite of the presence of shaly beds in the section is indicated by sinks in the Becraft, topographically as well as stratigraphically the highest formation in the group, which have no outlet except through the shaly New Scotland limestone, and springs in the Cobleskill, the lowest formation in the group. These springs have a volume of flow such that the water must have been obtained from gathering grounds on the Coeymans, and must have passed through the shaly Rondout. However, in some places these shaly formations have impeded the flow of water and springs have formed at their contacts with the overlying massive limestones. Examples include the spring north of Schoharie, at the contact of the Manlius and Rondout, that is part of the water-supply system of the village of Schoharie, and a spring on Dann's Hill west of Schoharie at the contact of the Becraft and New Scotland.

For the purposes of discussion it is convenient to distinguish caves accessible by natural openings in Schoharie County into "spring caves" and "sink caves." The former are those which discharge water continuously or intermittently, or discharged it at some time in the past; in other words, those which are the outlets of an underground drainage system. The latter are those which receive water, whether they are typical funnel-shaped sinks or merely horizontal openings along bedding planes through which water enters the ground. Commercially developed caves such as Howes and Secret Caverns represent median segments of an underground drainage system and do not fit into this classification, although it is believed that the original entrance to Secret Caverns was through a sink cave and that to Howes Caverns was through a spring cave. Of the large caves in Schoharie County, Ball's Cave, McPhail's Hole, and Ice Cave are examples of sink caves; and Clark's Cave, Becker's Cave, and an unnamed cave in the Onondaga southwest of Schoharie are spring caves.

The massive limestones become cavernous by enlargement of joints and bedding planes by solution. In certain areas, particularly just behind and on top of cliffs formed by the Manlius and Coeymans limestones, the joint cracks are up to a foot in width and six to ten feet deep. These areas are treacherous to walk over and are useless for farming, being commonly left as wood lots. There are all gradations between such enlarged joints and typical sinks, the largest of which is McPail's Hole, which is estimated to be about 70 feet deep and which has an H-shaped ground-plan controlled by joints. Groups of small sinks are commonly aligned along joint systems. No sinks were observed which might have been formed by collapse of caves.

The caverns formed in massive limestones tend to be rectangular in cross section, having flat roofs formed by bedding planes and more or less vertical walls. The caverns are commonly linear, with few side passages and little drip stone. Most of them contain, during at least part of the year, free-surface streams which are flowing on fairly well-graded beds and are enlarging their caves at the present time. The criteria suggested by BRETZ [1942] for caves formed below the water table, such as anastamosing channels, ungraded floors, box work, and other features showing simultaneous solution on all surfaces, have not been observed in the caves in Schoharie County. A possible exception to this is Ball's Cave, as described by GRABAU [1906], which has

an ungraded floor and other features suggestive of a phreatic origin. However, it is believed that although the caves in this area may have been initiated below the water table, the greater part of their enlargement has been by free-surface vadose streams, accompanied by quarrying of blocks from the ceiling along joint planes and solution by thin films of vadose water moving down joint cracks. It may be significant in this connection that wells drilled into the limestone below the water table have low yields, and deep wells in these rocks tend to have highly mineralized water, suggesting that openings below the water table are not large and circulation is poor.

All the large explored caverns in the massive limestones are in the Manlius and Coeymans formations, which together have a thickness of 100 feet. Although the Becraft and Cobleskill formations transmit water through solution passages and contain sinks and springs, respectively, they are too thin to permit the development of large caverns. The character of the passages transmitting water through the shaly limestones is not definitely known, unless Clark's Cave, just west of Schoharie, which emerges through the lower, more massive beds of the Rondout limestone, may be representative of this type. Unlike the caves in massive limestone, this has a more or less tubular cross section and is not noticeably controlled by joints.

Clark's Cave has previously been mentioned as an example of a spring cave, and it contains a stream of water except during the driest parts of the year. The principal spring of the Schoharie water supply, which emerges at the contact of the Manlius and Rondout limestones, has been shown in Figure 1 as a spring, although in times of low water it is possible to go nearly 200 feet into a cavern about six feet high. On the other hand, many of the springs which drain the limestone areas either emerge through openings too small to be entered or emerge through glacial drift which has concealed the original openings. The spring in the Cobleskill limestone at the village of Howes Caves, which is believed to drain Howes Caverns, is an example of the former; the supplementary spring of the Schoharie water supply north of Schoharie is an example of the latter.

In the limestone plateau region north of Howes Cave, and also in the region north of Gallupville, the direction of drainage through the limestones appears to be toward the south, down the dip of the formations, most of the sinks being near the northern edges of the plateaus. However, in the limestone terraces on either side of the Schoharie Valley, the drainage is parallel to the slope of the valley walls, and is determined by the joint systems. With few exceptions, the springs occur on hill slopes and may be classed as gravity springs. One of the exceptional cases is formed by the springs on the Shaw farm, between Barnerville and Cobleskill. These springs rise in deep circular pools, one of which is at the bottom of a steep funnel-shaped depression. No bedrock is exposed on the farm. The springs are reported to have cast up sawdust and other materials known to have entered the sinks south of Carlisle, and presumably are the outlet for the drainage of this part of the limestone region, as shown in Figure 1. These springs originally may have been gravity springs draining into the preglacial valley of Cobleskill Creek and may have been blocked and forced upward as artesian springs by the clayey glacial drift now filling the preglacial valley.

At Barnerville, east of Cobleskill, Cobleskill Creek flows across the Coeymans limestone, having been diverted from its preglacial valley farther north during the Pleistocene glaciation. The creek loses water into the limestone, and in the summer of 1946, the United States Geological Survey measured the flow above and below the limestone outcrop. The flow of 3.5 cfs above the outcrop was reduced to a flow of 0.15 cfs below the outcrop. Measurements farther downstream and estimates of the amount of water added by tributaries indicated that the water lost into the limestone at Barnerville was returned to the creek through the stream bed at some point between Barnerville and the village of Howes Cave. This condition suggests that at some future time a natural bridge may be formed at Barnerville.

The foregoing notes on the hydrology of the limestone areas in Schoharie County have been based on six weeks of field work on the ground water in the County as a whole. Further critical studies of the limestone areas are desirable, and may show more definitely how much of the cavern formation is vadose and how much phreatic, how much of the solution has occurred since the Pleistocene, and perhaps also the relationship of the caves to the 2000-foot peneplane developed on the overlying siltstones of the Hamilton group.

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PROGRESS IN GEODETIC SURVEYS BY THE UNITED STATES COAST AND GEODETIC SURVEY, JULY 1946 TO JUNE 1947

J. H. Brittain

Abstract--The field work of the Division of Geodesy of the United States Coast and Geodetic Survey from July 1, 1946 to June 30, 1947, has been principally to provide control for mapping for the Corps of Engineers, the United States Army, the United States Geological Survey, the United States Bureau of Reclamation, and the United States Forest Service. In addition to work for these organizations triangulation in Alaska and triangulation and leveling in the earthquake regions of California were resumed and control for urban survey projects has been undertaken on a cooperative basis. Altogether eight triangulation parties and three leveling parties totaling nine units have been working continuously throughout the year. Two triangulation parties worked through the summer of 1946 and were disbanded in the fall.

Triangulation and leveling started in 1944 in the Columbia River Basin for the Corps of Engineers were continued to the completion of control along the Snake, Salmon, and John Day Rivers in Wyoming, Idaho, and Oregon. Work has progressed in western Washington in the Cowlitz, Klickitat, and Wind River areas to the point where it can be completed in one summer by one triangulation party.

The triangulation in the Columbia River Basin is providing for the location of numerous supplemental stations and picture points for the use of photogrammetrists in addition to the main-scheme stations.

The triangulation party working in Alaska from May to October 1946, provided an arc of triangulation across the Alaskan Peninsula from Portage Bay on Shelikof Strait to Egegik on Bristol Bay, then along the south side of Bristol Bay northeastward to Kvichak Bay then straddling Kvichak Bay and River and Iliamna Lake continued northeast and east to a connection with existing triangulation in Cook Inlet. This arc provides control for charting the Bristol Bay waters and for mapping by the Fish and Wildlife Service. It is intended to extend triangulation this coming season westward along the north shore of Bristol Bay, locating supplemental stations for control for mapping from air photographs in addition to a main scheme. With the exception of a few stations in Cook Inlet where a hydrographic vessel was used, transportation of the Alaska party was by airplane.

Triangulation and leveling have been in progress for the Corps of Engineers in the Missouri River Valley, in the States of North Dakota, Nebraska, Kansas, and Missouri; the Trinity River Valley in Texas; and along the Black Warrior and Tombigbee Rivers in Alabama and Mississippi. In North Dakota, the work consisted of an arc from Minot to Devils Lake and triangulation and leveling along the Missouri River. In Missouri, triangulation has been executed along the Gasconade River and levels run in the western part of the State. The work in Kansas has consisted of leveling near Kansas City and triangulation along the Blue River. The triangulation in the Blue River area was started in April 1947.

During the winter of 1946-1947, triangulation has been completed along the Trinity River in Texas from Fort Worth southeast to Palestine. Considerable second order area leveling also has been done in this section of the State this past winter.

The work in the Black Warrior and Tombigbee River basins in Alabama and Mississippi has consisted entirely of leveling and reconnaissance for triangulation in the winter of 1946-1947. It is expected that triangulation will be undertaken in the winter of 1947-1948.

One triangulation party operated in western Nebraska during the summer months providing horizontal control for the U. S. Geological Survey. The work in this area consisted of arcs along latitude 42° and longitude 102° and area coverage south of the east-west arc to the North Platte River.

A triangulation party was engaged on triangulation in southern Mississippi in the winter of 1946 and 1947. This, as in the Black Warrior and Tombigbee River basins, is a winter project.

One leveling and two triangulation parties have been engaged on establishing control in Indiana, primarily for the U. S. Geological Survey. Work was discontinued in this area during the winter months and was resumed in the spring of 1947. One triangulation party is working in southern Indiana, one triangulation and leveling party in the northern part of the State.

In the winter of 1946 and 1947, a party completed triangulation in the Santa Clara Valley of California on a project started in 1944. In addition, a number of old stations in the general vicinity of San Francisco were reobserved for studies of Earth movements caused by earthquakes. This party after making repeat observations in earthquake regions in Southern California, is now engaged upon triangulation in the Mt. Hood National Forest in Oregon.

A leveling party comprised of three units has been engaged on area leveling in the Sacramento Valley in California for the U. S. Geological Survey. A unit of this party was engaged on leveling in Oregon and Washington on projects of interest to the U. S. Forest Service and the U. S. Bureau of Reclamation.

Horizontal control was provided for mapping by the Bureau of Reclamation during this period, one project in central Utah and one along the Rio Grande in Texas. The project in Utah was discontinued in November 1946 because of weather conditions and was resumed in June 1947. The project in Texas was completed in March 1947.

Triangulation was completed in the Tonto National Forest Area in Arizona for the U. S. Forest Service. That party was engaged on triangulation northwest of Phoenix in an area of interest to the Reclamation Bureau before moving to central Utah to resume work on that project.

A triangulation party has been working in Nevada on three projects requested by the State Planning Board of Nevada. The areas comprise highly developed regions about Reno, Las Vegas, and Winnemucca. This party recently started an arc of triangulation in northeastern Nevada.

Two projects providing for horizontal control for urban areas have been undertaken during this period on a cooperative basis with local organizations. These are located in (1) the East San Francisco Bay Municipalities and (2) the City of Cincinnati and Hamilton County in Ohio. The Coast and Geodetic Survey furnishes supervisory personnel, instruments and some equipment, and makes the office computations. The work in the San Francisco Bay region is nearing completion while that at Cincinnati will require six to eight months to complete.

These projects provide for base lines to adequately control the triangulation, some traverse and triangulation stations at about four-mile intervals over the areas. About 150 stations are required on the California project and about 80 in Ohio.

All triangulation provided during this period has been first order or modified second order accuracy. The modified second order triangulation is only slightly below first order, the same instruments and methods being used, but with maximum triangle closures of five sec being allowed to cut down on reobserving. The latter has been confined entirely to breakdown for supplemental stations or area triangulation tied rigidly to first order at frequent intervals.

Base lines have been measured at frequent intervals along the schemes of triangulation to control the lengths. Invar tapes were used for the purpose, their lengths being determined by the U. S. Bureau of Standards before and after the measurements. An astronomic party operated in the field until November 1946, observing azimuth, latitude and longitude at selected stations. Stations were occupied in New Mexico, Colorado, Idaho, Oregon, North Dakota, Missouri, and Indiana. The observations for latitude and longitude were made with the Bamberg broken-telescope transit. Observations also were made at each station with the pendulum astrolabe for the purpose of studying the accuracy of observation to be expected with that instrument. The computations of the results of these observations have not been completed but preliminary data indicate less accuracy than obtained with the Bamberg transit.

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EARTHQUAKE STUDY IN GREECE, 1947

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Since the instrumental records at the Seismological Observatory of the Institute of Athens were placed at the writer's disposal by the new provisional Director, E. Mariolopoulos, several attempts have been made to extend the research work by instrumental studies of earthquakes.

An attempt was made to use the seismograms to verify the field epicenter of the Chalcidique earthquake of September 26, 1932, and its larger aftershocks of September 28 and 29, of October 2 and 9, and of May 11, 1933, found by GEORGALAS and GALANOPOULOS [see "References" at end of report, 1946]. It is to be noted that the shock of September 26, 1932 on the east coast of Chalcidique is by far the largest shock of recent years in the Greek area.

As a first step it was recognized that the records of the shocks in question were insufficient to locate epicenters accurately enough for this purpose. For some of these shocks, especially for the main one of September 26, the microseismic data were found insufficient even to establish the region of occurrence owing to the throwing off of the recording pen. Such being the case, the writer turned to the use of the first impulse visible on the records for inferences regarding the initial movement at the focus, which in turn could eventually be suggestive of identical epicenters. This attempt has also failed for lack of data in various directions and at various distances. Moreover, the beginning of the records of most of the aftershocks mentioned above (especially that of the aftershock of October 2, for which another epicenter has been adopted [MARAVELAKIS, 1933]), is too small at the Athens station to be detectable with confidence. As it is well known [GUTENBERG, 1941], in such doubtful cases no sound conclusion regarding the first fault movement can be drawn regardless of the direction of the fault, as has been done by CRITIKOS [1942].

Another attempt has been made to confirm a previous conclusion of the writer that the true intensity in the epicentral region of the shock of March 1, 1941 was really not in excess of the eighth degree of the Mercalli-Sieberg scale [GALANOPOULOS, 1946]. This would be possible in a certain measure by calculating the magnitude of the shock; but such a procedure takes for granted the knowledge of the mean correction to be applied for the magnitude calculated from the records at the Athens station. As this correction represents the effects of ground and instrumental idiosyncrasies [GUTENBERG and RICHTER, 1942], it could be used to verify the reliability of seismograms available at the Athens station. However, because of a recent geological investigation, this is disputed [TRIKKALINOS, 1945]. This effort also failed because of the lack of instrumental constants since 1928. The same is true for the auxiliary station at the Seismological Laboratory of Athens University. The instrumental constants of this station are unknown since the installation of Mainka seismographs in 1934. Of course, under these circumstances the records at the last station can not be used for checking the seismograms available at the principal station at Athens.

The Wiechert seismographs of Athens Observatory, with long-period characteristics (mass, 1000 kg; period, 12 sec; magnification, 200), being suitable for recording distant earthquakes, often failed to record the large Greek earthquakes. This together with a small drum speed (13 mm/min) furnish, as it was to be expected, inadequate seismograms, in which often none of the impulses is clearly recorded. Also the uneven speed of the recording drum in combination with large irregularities in the daily rate of the clock makes the time marks on the records yield very inaccurate readings [SIEBERG, 1932]. All these events together with a bad installation and the effects of an extremely unfavourable structure beneath the station in Athens [TRIKKALINOS, 1945] make every investigation unreliable based on the seismograms available at the principal station of Athens. This, of course, is more true for the study of deep focus earthquakes [CRITIKOS, 1948], even by considering time corrections of doubtful accuracy. The instrumental records at the Seismological Laboratory of Athens University are as bad as those at the Seismological Institute of Athens Observatory, or worse. Differences in the readings at these seismological stations in Athens have been found to be beyond the limits of error in several instances.

In order to give a clearer picture of the seismological conditions in Greece it should be noted that in 1939 the clock was connected with the municipal electric current. Thus, during the occupation, owing to frequent interruptions of the electric current, nearly all records are without time

marks. The same is true for most of the seismograms available at both Athens stations after the liberation. Fortunately the principal station has lately been provided with storage batteries to replace the municipal electric current. It is to be noted that now the library of the Seismological Laboratory of Athens University as well as that of the Seismological Institute of Athens Observatory are in great want of most of the "Publications du Bureau International" and of the "International Seismological Summary" (with the exception of the years 1933 and 1935), which are needed for comparing the readings at the stations in Athens with those reported by other stations. The instrumental data of Athens Observatory are unpublished since 1928. The routine analysis of seismograms during this time has never been done.

It would be desirable if immediate steps could be taken to restore the network of macroseismic observations that have been disarranged since the time of occupation, and to install short-period vertical seismographs suitable for use in the very active area of Greece.

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REPORT OF THE COMMITTEE ON EVAPORATION AND TRANSPIRATION, 1946-1947

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In past years it has been the practice of this Committee for each member to report on the progress of his own research or of work with which he is acquainted, so as to provide a convenient compilation of current research on evaporation and transpiration. This method has seemed to be reasonably successful, but it has handicapped some of the members who were not conducting or in direct contact with active research. Therefore the members were asked this year to take part in a kind of symposium, writing on the relative contributions of evaporation and transpiration to total water losses, as affected by vegetation. The results are presented below.

E. A. Colman (California Forest and Range Experiment Station, Berkeley, California)--Some years ago members of the California Forest and Range Experiment Station considered making studies of evaporation and plant transpiration for the purpose of establishing the magnitudes of each type of soil water loss. The only field method that appeared feasible involved measurement of gross evapotranspiration losses by periodic soil moisture sampling, and concurrent measurement of transpiration losses from the vegetation. Evaporation would then be calculated as the difference between gross evapotranspiration and transpiration alone. Gross evapotranspiration could be measured without difficulty but we found no satisfactory method for the measurement of water losses from the vegetation canopy. A number of approximate methods have been proposed and used by research workers but none of those we studied appeared to offer a reliable means for the calculation of transpiration values on a ground-area basis.

Further discussion has led to the conclusion that the separation of evaporation from transpiration, in semi-arid California at least, is primarily of academic interest. In any plant community with which we have to deal, both processes are going on and their relative magnitudes vary with the character of the vegetative cover.

A bare soil devoid of plant roots presents a condition in which direct evaporation is the only factor. We have a good deal of evidence upon the magnitude of evaporation under this condition. Bare, trenched plots in southern California mountains (San Dimas Experimental Forest), in which soil moisture has been measured over a three-year period, show evaporation losses almost to the wilting point, extending to a depth of five feet. Much lower moisture losses were found in similarly treated plots in the Bass Lake area of the Sierra Nevada. Here the greatest part of the water is lost from the top two feet. Land supporting a stand of native vegetation presents a different picture. Soil moisture in the brush covered plots of the San Dimas, and the brush plots and pine plots in the Bass Lake area, was drawn down to the wilting point throughout the full soil depth each year.

In watershed management in the semi-arid West, we are concerned with vegetation management which will hold evapotranspiration to a minimum while providing adequate runoff and erosion control. As vegetation density and height increase it is probable that direct evaporation from the soil decreases, both caused by the shading afforded by the canopy and the rapid absorption by the plants of water in the upper soil layers. There may be a critical cover density corresponding to a minimum loss by evapotranspiration. On one side evaporation loss decreases as density increases; on the other side transpiration decreases as density decreases. The density at which the combined evaporation and transpiration is a minimum would be optimum so far as evaporative soil water losses are concerned. For the purpose of determining the critical density it is not necessary to measure evaporation and transpiration separately, but merely to measure total evapotranspiration losses from the soil.

A. R. Croft (Intermountain Forest and Range Experiment Station, Ogden, Utah)--In 1944 a study of evapotranspiration loss from Farmington Creek at the Wasatch Branch Experiment Station gave some indication of the relative amounts of water lost by stream-surface evaporation and by transpiration of riparian vegetation. The relative loss by transpiration and stream-surface evaporation was indicated by comparing flow of the stream, during the fall period of low temperatures that killed leaves, with rates of stream-surface evaporation.

Mean daily discharge increased about 0.9 cfs between September 10 and October 16. Leaves were killed by frost on October 16, and mean daily increases of 0.5 cfs and 0.25 cfs, respectively, followed immediately. The lowest temperature of the period occurred on September 15, but only a few leaves were frozen and the flow increase was small. This marked increase in flow of the stream following death of leaves by freezing indicates heavy loss of water by transpiration.

The fragmentary evaporation data for the period are not very well correlated with streamflow. About October 1, when flow increased approximately one-half cfs, the stream-surface evaporation rate was reduced by half, but during the flow increase about October 16 the rate remained about constant. Then, too, while flow remained about constant from October 9 to 11,, evaporation fluctuated more than 200 per cent. In addition, on October 16 when streamflow had increased 0.9 cfs the evaporation rate was still about one-third of the early Septebmer rate at the time the flow increase began. Finally, it seems unlikely that the difference between the day-time and night-time of evaporation, in early September, can account for more than minor influence on the diurnal fluctuations in streamflow.

Although the data are by no means conclusive, they at least suggest that transpiration is the principal factor in loss of water from Farmington Creek.

S. T. Harding (Consulting Engineer, Berkeley, California)--It is very difficult to measure evaporation and transpiration separately on areas growing vegetation. There are reasonably adequate results on evaporation from bare soils both in records of its amounts and the effect of varying moisture conditions. There are similarly many records of combined evaporation and transpiration from areas having vegetation.

Efforts have been made to measure evaporation and transpiration separately. The usual method has been to try to reduce the evaporation to zero. In this class of work would be included tank observations with the soil surface sealed with paraffin after the plants were up. This was probably effective in reducing evaporation to a negligible amount but its disturbance of aeration or other factors resulted in the plant growth being abnormal so that the results for transpiration were probably not representative of field conditions.

Another method was the introduction of the water supply below the surface within reach of the plant roots but deep enough so that capillary rise to the surface would be relatively small. This preserved natural conditions and the measured losses of moisture could be properly charged to transpiration. Evaporation after initial surface soil drying would be negligible if the tanks were protected at times of rains from further soil wetting.

While the introduction of water below the surface may enable transpiration to be measured with an evaporation so small that it can be neglected, this method only produces transpiration. It does not aid in getting the evaporation under normal crop conditions. An effective experimental procedure which can reproduce the variable conditions of crop shading on evaporation and still measure evaporation has not yet been devised.

Viewed from general considerations, the ratio of evaporation to transpiration is widely variable. For irrigated alfalfa with a good stand the moisture use is dominantly transpiration. Most of the moisture evaporates when sparse desert vegetation receives only occasional rain with its usual limited depth of penetration. Quantitative results for various degrees of density and amount of growth between these limits will be useful, but much generalization in their applications will be needed even when adequate observational results may become available.

M. D. Hoover (Southeastern Forest Experiment Station, Asheville, North Carolina)--With the exception of evaporation from snow, moisture lost to evaporation and transpiration is withdrawn from the soil and the quantity lost is related to the available soil moisture. Both processes cease when the soil is dry and both can increase in rate with increasing soil moisture. However, evaporation removes moisture primarily from the surface of the soil and proceeds at a low rate after a thin surface layer of soil has been dried. Transpiration removes water to considerable depths and the process may continue until no available moisture remains throughout the root zone. For this

reason, transpiration is a relatively more important source of moisture loss on deep soils than it is where soils have a depth of 12 inches or less. It is also a relatively larger loss when summer rainfalls are heavy enough to moisten the entire root zone than it is if summer rainfall occurs in light showers which wet only the soil surface.

Because we know very little about the loss factors on a watershed basis, generalizations are risky but I can give some observations made at the Coweeta Experimental Forest, located in western North Carolina. Rainfall here is abundant and well distributed throughout the year. Snow seldom occurs and when it does it melts rapidly. We are measuring rainfall and runoff for 30 small watersheds within a six-square-mile basin. Considerable differences in total water loss (P-RO $\pm$S) have been observed between areas and are seemingly associated with soil depth as it affects retention storage of water. The greatest total losses occur where storage is greatest. Table 1 shows the difference in total water loss between two watersheds of different storage characteristics with an estimate of how we believe this loss is distributed among the individual loss factors. The method of deriving the sources of loss has been previously described [see "References" at end of report, HOOVER, 1944].

Table 1--Amount and distribution of average annual water loss; Coweeta Experimental Forest

Watershed character	Interception		Transpiration		Evaporation		Total annual water loss
	Depth	Loss[a]	Depth	Loss[a]	Depth	Loss[a]	
	in	pct	in	pct	in	pct	in
Deep soil	7	17	19	45	16	38	42
Shallow soil	6	21	10	36	12	43	28

[a]Per cent loss = percentage of the "total annual water loss."

Variations in water loss also occur from year to year. Maximum water losses are induced by abundant summer rainfall which recharges the root zone favoring high rates of transpiration. Reduction of vegetation density reduces the amount of loss during such periods. Minimum total water loss is a result of abundant winter precipitation followed by a summer of low rainfall.

For each watershed there is some combination of the individual losses which will result in the minimum total loss. As yet at Coweeta, we do not know this answer but we have treated watersheds so that total yield is greatly increased [HOOVER, 1944]. By cutting all vegetation on a 33 acre watershed and spreading the cut material over the surface to form a mulch, the results given in Table 2 were obtained the first year after cutting.

Table 2--Water economy for Coweeta Area No. 17; comparison of results after cutting with estimated values had vegetation been undisturbed from April 1, 1941 to March 31, 1942

Item	With vegetation cut	With vegetation undisturbed
	area in	area in
Precipitation	62.4	62.4
Runoff	36.8	19.3
Change in ground-water storage	+ 3.9	+ 2.6
Total water loss	21.9	40.5
Interception	3.7	6.4
Evaporation from soil	18.2	15.1
Transpiration	. . .	19.0

Interception was not completely eliminated by this cutting because the mulch was about as effective in intercepting rainfall as had been the previous hardwood stand during the leafless winter condition. Because sprout growth was cut back during the first summer season, transpiration was eliminated in 1941 and the total loss was made up entirely of interception and soil evaporation. Sprout growth is vigorous, and in four growing seasons trees attained heights of from 4 to 15 feet and the dense coppice stand was transpiring 13 inches of water.

I. Kittredge (University of California School of Forestry, Berkeley, California)--The total losses effected by vegetation include transpiration, evaporation from the soil, and interception. Although the latter is an evaporative process, it is not included in evaporation in what follows. From bare soil, transpiration is zero and the total losses are equal to the evaporation, and $T/E = 0$, representing one extreme. At the other, when the vegetation is at a maximum, transpiration is maximum and evaporation is minimum although greater than zero. In this case, the rato T/E is maximum.

Transpiration draws moisture from the whole depth of the root zone. Evaporation reduces the moisture appreciably only in the upper foot of soil, except when there is freezing and thawing.

Evaporation decreases rapidly as the soil near the surface becomes dry. On the other hand, transpiration does not decrease with decreasing soil moisture until at least a part of the soil is below the wilting point. Therefore, as the soil becomes drier the ratio T/E will tend to increase.

In the absence of rigorous determinations of concurrent evaporation and transpiration, the following figures from the Swiss streamflow experiment in a mountainous region receiving 65 inches annual precipitation give an indication of the relative amounts under different vegetation. In the drainage basin with forest of Norway spruce, transpiration was 46 per cent and evaporation 18 per cent of the total losses. In the adjacent basin with two-thirds of its area covered with closely grazed grassland, transpiration was 21 per cent and evaporation 47 per cent of the total. Thus in the forested condition the transpiration was almost half the total losses and was more than twice the evaporation. In the two-thirds pasture area, evaporation was almost half the total and was more than twice the transpiration. Even allowing for some error in the admittedly approximate figures, the difference in vegetation resulted in a difference in the ratio T/E from 2.6 to 0.45.

The fact that transpiration and evaporation change in opposite directions with changes in age, size or density of the vegetation, suggests the need of more knowledge of their relative magnitudes in planning treatments of the vegetation to minimize the losses.

H. J. Lutz (Yale School of Forestry, New Haven, Connecticut)--On the subject of the relative contributions of evaporation and transpiration, as affected by vegetation, I have no data of my own. After examining the literature where one might look for material I have found two references; abstracts are given below:

WILLOMITZER, A., Wildbach und Lawinenverabauung, in Der Forstbetriebsdienst, Lehrbuch für den gehobenen Forstdienst, Second ed., by H. Weber and K. Orth, J. Neumann, Neudamm, Berlin, pp. 579-604, 1942. The greatest retarding influence, which becomes exhausted only after unusually protracted precipitation, is attributed to the forest. With its canopy and root zone it exerts an influence in runoff regulation and protection against erosion that is equalled by no other form of plant community. In this sense, areas covered with dwarf mountain pine or green alder (Alnus viridis) must also be considered as forest. Of 100 per cent precipitation, the following amounts are withheld: (1) Through evaporation from the canopy, 10 to 35 per cent; (2) through evaporation from the soil, 5 to 10 per cent; (3) through consumptive use by vegetation and soil absorption, 20 to 25 per cent; total, 35 to 70 per cent. Runoff thus fluctuates between 30 and 65 per cent. The average value may be set at 45 per cent (from p. 583).

BROOKS, C. E. P., The influence of forests on rainfall, Empire Forestry Journal, v. 6, pp. 210-218, 1927, suggests that two-thirds of the rainfall over land is caused from water vapor from the sea. Estimates 15 per cent of rainfall is intercepted by forest vegetation (deciduous). Assuming a region in temperate latitudes with a rainfall of 30 inches, estimates loss by evaporation from soil as follows: Forest (with litter) seven per cent of rainfall; field crops 17 per cent; bare soil 30 per cent. Transpiration losses: Forests 25 per cent; field crops 37 per cent.

Summing up, additions of water vapor to air, in percentages of moderate rainfall in western and central Europe are shown in Table 3.

Conclusions--(1) Replacement of forests by crops or grass land tends to increase general rainfall slightly; their replacement by bare ground tends to decrease it slightly. (2) Forests increase local rainfall by one or two per cent. (3) Forests may, in favorable situations, increase water by mechanical collection. (4) Replacement of forest by crop land should decrease runoff by five to seven per cent of the rainfall, or ten to fifteen per cent of the runoff. This is likely to be the most noticeable effect of deforestation.

Table 3--Summary of evapotranspiration losses in per cent

Type	Forests	Crops	Bare soil
Evaporation from foliage	15	..	..
Evaporation from soil	7	17	30
Transpiration	25	37	..
Total	47	54	30

These values are stated to refer to deciduous trees. Brooks states that ". . .for conifers (a), evaporation from foliage is probably greater, (b) and (c) slightly less, the total probably about the same."

H. G. Wilm (Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado)--As pointed out by other contributors to this report, it is not easy to segregate the relative amounts of water consumed by evaporation and transpiration, though the sum of these two components of water loss may be obtained with reasonable precision by any of several methods.

Studies conducted at this Station tend to indicate that, in the central Rocky Mountains, interception by the forest canopy forms the main influence of a lodgepole pine forest on water losses by evaporation and transpiration. When this kind of forest cover was thinned by timber cutting, interception was greatly reduced, while any reductions in transpiration tended to be offset by increases in evaporation from the soil [WILM, 1944]. These studies led to the conclusion that the largest part of any gain in water yield resulting from timber removal could be charged to reductions in interception of snow and rain, especially snow. A similar conclusion was reached by BATES and HENRY [1928], in the Wagon Wheel Gap watershed experiment in Colorado.

References

BATES, C. G., and HENRY, A. J., Forest and streamflow experiment at Wagon Wheel Gap, Colorado, Mon. Wea. Rev. Suppl., no. 30, 1928.

HOOVER, M. D., Effect of removal of forest vegetation upon water yields, Trans. Amer. Geophys. Union, pp. 970-975, pt. 6, 1944.

WILM, H. G., The effect of timber cutting in a lodgepole pine forest on the storage and melting of snow, Trans. Amer. Geophys. Union, pt. 1, pp. 153-155, 1944.

Other pertinent literature

COLMAN, E. A., A laboratory study of lysimeter drainage under controlled soil moisture tension, Soil Sci., v. 62, pp. 365-382, 1946.

HALDEN, BERTIL E., Influence of forest stands on the distribution of soil moisture in various soils, Skogsvards Föreningens Tidskrift, v. 24, pp. 125-243, 1926; Forest Service Translation, No. 367-A by S. C. Andersen, 1936.

LUTZ, HAROLD J., and CHANDLER, ROBERT F., Forest soils, John Wiley and Sons, Inc., 514 pp., illus., 1946.

(Manuscript received April 15, 1947; presented at the Twenty-Eighth Annual Meeting, Washington, D.C., April 29, 1947; open for formal discussion until September 1, 1948.)

Transactions, American Geophysical Union Volume 29, Number 2 April 1948

REPORT OF RESEARCH COMMITTEE ON RUNOFF, 1946-1947

R. W. Davenport, Chairman

W. C. Ackermann
Bertram Barnes
Merrill Bernard
Bruce R. Colby
Howard L. Cook
E. S. Cullings
G. A. Hathaway
W. G. Hoyt
C. R. Hursh
Carl F. Izzard
Karl Jetter
Phillip Light
Charles C. McDonald
F. T. Mavis
C. E. Ramser
L. K. Sherman
Waldo E. Smith
F. F. Snyder
H. G. Wilm

The membership of the Committee has remained unchanged during the year. There has been some discussion of committee activities between individual members and in small groups. The further discussion of runoff terminology has resulted in no new developments of special note.

The following statements have been received from members of the committee concerning activities of the agencies with which they are associated.

Franklin F. Snyder (Office of the Chief of Engineers, Washington, D. C.)--In addition to routine investigations of runoff that are necessary for preparation of reports and for planning and operation of flood control and river and harbor projects, the Corps of Engineers is carrying on the following special investigations:

(a) The mountain snow laboratories in the west, carried on cooperatively with the United States Weather Bureau, are continuing to function. Processing and analysis of the data are being carried on concurrently and technical reports based thereon are being prepared.

(b) The Louisville District of the Corps of Engineers has been carrying on an investigation of rainfall-runoff relations for sewered areas on the Beargrass Creek drainage basin and four sewered areas at Louisville. The investigations were initiated in 1944 for the purpose of developing methods for computing design-storm discharges from the Beargrass Creek area and typical sewer systems for pumping plant design. Discharge records for nine areas varying in size from 60 ac to over 50 sq mi have been collected. Precipitation data from 18 recording and two non-recording rain gages are available. Unit hydrograph and other techniques for computing discharge hydrographs have been utilized in analyzing the basic data. A preliminary report on the results of the investigations is expected to be completed by July 1947.

(c) For two years the Ohio River Division of the Corps of Engineers has carried on an investigation to establish the validity of, or necessary revisions to, current procedures of design for surface drainage facilities at airfields. Rainfall records and flow data have been collected from 14 areas at Wright and Lockbourne Airfields in Ohio, Freeman and St. Anne Airfields in Indiana, and Godman Airfield in Kentucky. Collection of field data is about completed with analysis of the material and preparation of a report to be finished by July 1947. Similar investigations have been initiated at Pine Castle Army Airfield in Florida and at Santa Monica Municipal Airport in California.

(d) The New England Division of the Corps of Engineers is carrying on a turf-drainage investigation to determine satisfactory methods, structures, and design criteria for construction of turf runways and turf-base drainage. A test section has been completed at Fort Ruckman, Massachusetts, and observations of rainfall, surface and subsurface runoff, and ground-water conditions are in progress.

C. F. Izzard (Public Roads Administration, Washington, D. C.)--Analysis of the data obtained in the cooperative investigation of overland flow previously reported has been completed during the past year. In addition, analytical studies have been made of routing of overland flow through gutter storage. These analyses are abstracted in a paper on "The Hydraulics of Runoff from Developed Surfaces" which is being published in the Proceedings of the Highway Research Board

for 1946. The paper presents a new method of computing the outflow hydrograph based on dimensionless curves for the rising and falling limbs of the hydrograph and on the principle of momentum for the magnitude of the peak flow. The method has recently been applied to runoff from a turf swale on an airfield and found to yield results closely similar to those obtained by detailed routing computations. The magnitude of the peak rate of runoff was found to be very sensitive to variation of the roughness factor with the depth of flow in the turf channel. The roughness factor was based on experimental data on vegetated waterways reported by PALMER [see "Reference" at end of report, 1945]. This suggests a need for further experimental data on vegetated-channel roughness where the cross-section is triangular, as in an airport swale, instead of being of uniform depth.

An investigation of storm-water drainage for highways is about to start at the University of Illinois as a cooperative project of the State Highway Department and the Public Roads Administration. While the initial efforts will be concentrated on development of inlets for use on urban express highways, the investigation will also include study of runoff in urban areas.

A cooperative project of the Minnesota Highway Department and the Public Roads Administration has started at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota for fundamental research on the hydraulics of culverts. This investigation will include design of entrances and exits to minimize erosion and design of entrances to improve hydraulic characteristics over the entire range of flow. Damage by ponding at culvert entrances can be reduced if the culvert discharges efficiently during the early part of the flood flow, thus leaving more storage capacity for absorbing the peak flow without excessive depth of ponding.

The Proceedings of the Highway Research Board for 1946 also include a paper by Dalrymple on use of stream flow records in design of bridge waterways, a paper by Krimgold on hydrology of culverts, and a paper by Erickson on scour at a Mississippi River bridge pier.

C. E. Ramser (Soil Conservation Service, Washington, D. C.)--The hydrologic activities of the Soil Conservation Service have continued about the same as reported for last year. Manuscripts have been prepared but have not yet been published covering past runoff investigations on small watersheds in Maryland, Virginia, New Jersey, New York, and Ohio, with recommendations for rates and amounts of runoff for the design of soil and water conservation structures. The following articles were published during the past year:

(1) The Effect of Conservation Practices on Peak Rates of Runoff, by Ralph W. Baird, Texas Engineer, August 1946.

(2) Some of the Flood Control Aspects of Farm Ponds, by A. W. Zingg, Agricultural Engineering, January 1946.

(3) Relationships that Simplify Hydrologic Design of Ponds, by W. D. Potter and D. B. Krimgold, Agricultural Engineering, June 1946.

(4) Rates of Runoff from Small Drainage Basins, by D. B. Krimgold, Agricultural Engineering, January 1947.

(5) Runoff Behavior of Small Agricultural Watersheds under Various Land Use Practices, by Harold W. Hobbs, Transactions, American Geophysical Union, February 1946.

(6) The Influence of Treatment and Slope Length on Rates of Runoff from Collington Sandy Loam, by O. R. Neal and C. C. Butler, Transactions, American Geophysical Union, December 1946.

The publication of hydrologic data as carried on before the war has not yet been resumed, principally because precedence has been given to a backlog of regular publications of the United States Department of Agriculture that were dispensed with during the war.

Merrill Bernard (United States Weather Bureau, Washington, D. C.)--In the past year there has been a series of basin maps on which is shown the nation-wide network of hydrologic stations. These maps were prepared under the auspices of the Subcommittee on Hydrologic Data of the Federal Inter-Agency River Basin Committee. The network of stream-gaging stations operated by the United States Geological Survey together with the network of precipitation stations are combined for the first time in a complete set of maps. Ultimately, the map series will serve as the basis for extending these networks into poorly represented areas and will include other types of hydrologic stations such as those observing evaporation, ground water, and soil moisture.

In an expansion of its river and flood forecasting program the Weather Bureau has established consolidated River Forecast Centers at Cincinnati, Ohio, and Kansas City, Missouri, to serve the Ohio River and the lower Missouri River Basins, respectively. These forecast centers are staffed with professional hydrologists, who in the past several months have been engaged in the development of objective forecast procedures for their areas. Forecasting techniques have been developed which have made it possible to extend the service into headwater areas.

R. W. Davenport (United States Geological Survey, Washington, D. C.)--During the past year the Geological Survey has continued to expand its stream-gaging program in cooperation with numerous Federal agencies, the 48 States, the Territory of Hawaii, and many municipalities. Table 1 shows the number of gaging stations at five-year intervals for the past 25 years. The number has nearly quadrupled in 25 years.

Table 1--Number of stream-gaging stations operated by the United States Geological Survey in cooperation with other agencies[a]

Year	Number of stations	Year	Number of stations
1922	1540	1937	3379
1927	1749	1942	4966
1932	2791	1947	5977

[a]All June 30 except 1947 which is January 1

In connection with studies for the improvement of the Water Resources Review, considerable progress has been made in the adoption of normals for stream flow based on a uniform period of time, 1921-1945. This has involved the application of standardized procedures for inserting missing records and extrapolating backward as necessary to complete the 25-year record by means of procedures of statistical correlation which have been developed.

During the year the Geological Survey has taken steps to stimulate research activities of its organization in the field of runoff that will be useful in promoting more economical design of bridge and culvert openings. These activities include the listing and statistical analysis of floods, a larger representation of gaging stations on small drainage areas, and adaptation of hydraulic data obtained in stream gaging to use in bridge and culvert design. It is expected that this program will be of special value to state highway departments. The program conforms generally to recommendations of the Highway Research Board. Tate Dalrymple has been assigned to coordinate this program.

The following reports contributing to some phases of runoff research have been issued by the Geological Survey during the year:

(1) Water-Supply Paper 915, Major winter and non-winter floods in selected basins in New York and Pennsylvania by Walter B. Langein and others,

(2) Water-Supply Paper 994, Cloudburst floods in Utah, 1850-1938 by Ralf R. Woolley,

(3) Water-Supply Paper 996, Geologic features of Connecticut Valley, Massachusetts, as related to recent floods by Richard H. Jahns.

The Committee on Hydrology of the American Society of Civil Engineers is sponsoring a manual on Hydrology, which includes a chapter on runoff. The second draft of this chapter has been prepared and submitted for review to a subcommittee consisting of C. F. Izzard, S. W. Jens, W. B. Langbein, R. K. Linsley, E. P. Schuleen, and H. C. Troxell. It was understood that final submission of the manuscript was scheduled for September 1, 1947.

Reference

PALMER, V. J., A method of designing vegetated waterways, Agric. Engr., v. 26, no. 12, pp. 516-520, 1945.

U. S. Geological Survey,
Washington, D. C.

(Manuscript received May 13, 1947; presented at the Twenty-Eighth Annual Meeting, Washington, D. C., April 30, 1947; open for formal discussion until September 1, 1948.)

REPORT OF COMMITTEE ON LAKES, 1946-1947

P. E. Church, Chairman

There have been several changes in the membership of the Committee during the past year. At present the Committee is composed of the following: G. Benton, J. L. Hough, C. S. Howard, G. E. Hutchinson, N. A. Riley, Ralf R. Woolley, and P. E. Church (Chairman). Each of the above members has a definite field of interest in limnology as follows: Hydrometeorology, sediments, various features of artificial lakes, general chemical limnology, shore features and deposits, chemical changes of artificial and natural lakes, and thermal characteristics.

One important item of business has come before the Committee and, as yet, has not been properly consummated. The Executive Committee of the Section of Hydrology, in its action of May 24 and 27, 1946, authorized the Chairman of this Committee to appoint three reporters to prepare American reports on the topics below for inclusion on the program at the General Assembly of the International Union of Geodesy and Geophysics in Oslo in 1948. The topics proposed are: (1) Water balance of lakes, including inflow, outflow, precipitation, and evaporation; (2) statistics of lake levels, with special reference to magnitude and duration of fluctuations; and (3) movement of water in lakes.

Thus far no one has accepted the responsibility of becoming a reporter and preparing the necessary report, other than for the first topic. It is hoped that acceptances to invitations to become reporters for the last two topics will shortly be forthcoming.

Because of the wide geographical distribution of the members it has been impossible to have a Committee meeting, but the Chairman has contacted several in person, has corresponded with other members, and has discussed certain limnological problems with others in bordering fields. There clearly exists general unanimity that in this country limnology in all its phases is in an unorganized condition. The Committee feels that some of its responsibility is to help direct limnology toward better organization by clarification of objectives and scope, cooperation between the workers in various fields in limnology, dissemination of information regarding research projects in progress, suggested fields to explore via research, a bibliography brought up to date and continued in the future, and possible outlets of employment for those trained in limnology.

Further, there is the danger that the purely physical and biological groups may become more widely separated than at present. Much sound physical limnology has been performed in the past by biologists. It would be well to consider some affiliation or other connection with the Limnological Society of America which consists mainly of biologists. It has also been suggested that limnology might well become a separate section of the American Geophysical Union.

University of Washington,
Seattle, Washington

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COLUMBIA RIVER STUDIES IN CANADA

C. E. Webb

Pursuant to the reference dated March 9, 1944, to the International Joint Commission by the Governments of Canada and the United States, the International Columbia River Engineering Board was appointed by the Commission to investigate and report upon the feasibility of further development of the water resources of the Columbia River Basin. The Board is made up of four members, two from each country.

In order to expedite the investigations the members of the Board designated representatives from associated offices on the West Coast to take charge of field operations and assist the Board in its studies. These representatives form the four-man International Columbia River Engineering Committee.

While some investigations of the water resources of isolated portions of the Columbia River system in Canada have been made for various purposes, there has been no overall survey of the complete water resources of the basin in Canada such as was made by the Corps of Engineers, United States Army, in the compilation of the Columbia River 308 Review Report. This report covered a thorough study embracing the resources of the entire Columbia River system in the United States. The authorization of the present study of this great river system, therefore, represents in the United States the furtherance and continuation of the fundamental work included in the 308 Review Report; in Canada it represents both the securing of basic and fundamental data, and the furtherance and continuation of these studies. In other words, this investigation is well advanced in the United States, while to date it is only in the preliminary stages in Canada.

In the spring of 1945, a full-scale field program was put under way, including aerial photography, precise levelling, topographic mapping, reconnaissance surveys, hydrologic studies, bathymetric surveys, and dam site investigations. Aerial photography of the Columbia River and all of its tributaries in Canada was commenced in April, 1945, by the Royal Canadian Air Force. The coverage of the photographs is to extend to a minimum elevation of 500 feet above the valley floor along all of the principal streams in the Basin. To ensure satisfactory results, photography is restricted to the low water periods and to the times when snow is absent from the lower levels; hence the periods suitable for this phase of the investigation are quite brief. In spite of these limitations, the photographic program is now virtually completed except for the Big Bend area of the Columbia River, where weather conditions during the low water periods have so far precluded completion of the photographic coverage. Completion of the photography will be accomplished as weather permits.

Extension of the existing precise level net to cover the entire Columbia River Basin in Canada was continued by the Geodetic Service of Canada and they have now completed the work required. This required the running of over 500 miles of new and check-level lines. In addition to new ties to the United States level systems a number of the previous ties were remade, looking to elimination of differences in the elevations along the International Boundary which exist between the level nets of the two countries.

Topographic mapping required by this investigation has been carried out by the Hydrographic and Map Service of Canada. This required surveys of a vast part of the valley in Canada of the main Columbia and its principal tributary the Kootenay River. Areas which have been covered already by other organizations, such as the West Kootenay Power and Light Company, are not likely to be remapped. The information being obtained is sufficient to ensure accurate contour intervals of from two to 20 feet on map scales varying from 1000 feet to one-half mile per inch, depending on the character of the terrain.

Reconnaissance surveys of the main stem of the Columbia River and most of its tributaries in Canada are still required to obtain more information regarding potentialities. Those observed on reconnaissance may then be subjected to more detailed study where such treatment appears to be warranted. Prior to 1945 reconnaissance surveys had covered only a few scattered reaches of the

Columbia River in Canada. Since that time, reconnaissance surveys have been or are being completed along the Kootenay River from its headwaters to the International Boundary near Newgate, the St. Mary, Lardeau and Duncan Rivers, the Upper Columbia River from Columbia Lake to Windermere, the outlet of Lower Arrow Lake, and a number of minor tributary streams. Extension of this phase of the investigation to include a number of reaches of the main stem of the Columbia River is planned for 1947.

In connection with the surface-water phase of the necessary hydrologic investigations the Dominion Water and Power Bureau has, in the course of the past 36 years, established a comprehensive system of stream-gaging and water-elevation stations in the Columbia River system in Canada. However, to obtain the complete coverage of the water resources of the basin required in an investigation such as that now in progress, it has been necessary to extend this work and up to the present it has been considered necessary that over forty new gaging stations should be established as well as a number of additional water-elevation stations. This work is proceeding and to date 23 new gaging stations have been established or old stations improved as well as a number of water-elevation stations installed.

Records obtained at these stations designated as international gaging stations by agreement between our respective governments are accepted and published on the same basis as those of the other. This co-operation has been a decided asset to the study and solution of stream-flow problems along the International Boundary, and of particular value to the various Boards of Control who administer the orders of the International Joint Commission on certain designated waters, such as the International Kootenay Lake Board of Control, composed of representatives of the Corps of Engineers, United States War Department, the United States Geological Survey, and the Dominion Water and Power Bureau.

Prior to 1945, the ground-water phase of the hydrologic studies in the Canadian portion of the Columbia Basin had not been given much consideration. However, we now are carrying on comprehensive studies in the Kootenay Flats near Creston and in 1947 commenced similar studies in the Upper Columbia Flats above Golden as well as limited studies of the ground water throughout the whole basin. These latter studies, at present in a preliminary stage, will probably be extended if results warrant.

A program of soil surveys has been initiated in those areas of the Columbia River Basin which are of potential value as agricultural lands. Substantial progress has been achieved during 1946, and continuation of these studies is planned for 1947.

The Dominion Department of Public Works is conducting the necessary bathymetric surveys at the north and south ends of Kootenay Lake and on its west arm. In addition, similar surveys are to be extended to the Narrows between the Upper and Lower Arrow Lakes and the Columbia River from Lower Arrow Lake to the International Boundary. Horizontal control for these underwater surveys is in many cases being supplied by the Hydrographic and Map Service of Canada and in other cases by shore parties of the bathymetric survey. The result will be that both surface and underwater maps will be on a common control.

Owing to the paucity of information available regarding possible dam sites on the Columbia River system in Canada, detailed site investigations could not be commenced until reconnaissance surveys had been made to determine possibilites. In consequence, investigations during 1945 were limited to the Gibraltar Rock site on the upper Kootenay River, 18 miles upstream from Canal Flats. At this site a preliminary survey and drilling program was conducted, and a preliminary geological examination was made in 1946. When investigations in this area are more advanced, it is planned to extend operations to sites on the Kootenay River near Torrent and Wardner, and on the Lardeau and Duncan Rivers. Preliminary geologic examinations were made at these sites during 1946. Drilling operations are now being carried out by the Department of Public Works, Canada.

Systematic additions to the present meteorologic and snow-survey coverage of the basin are being planned, with 14 new snow courses scheduled to be put in operation during 1947 and 1948. This latter work is being done by the Water Rights Branch of the British Columbia Department of Lands and Forests, in cooperation with the Dominion Water and Power Bureau. The latter organization secured a Tucker Sno-Cat during the present year and this equipment will be of value not only in collecting stream flow data but also in making snow surveys in the Big Bend area of the Columbia which is almost inaccessible during the winter season.

Office studies in correlation of the data being obtained from the field are continuing with the constant receipt of additional information. These studies are increasing with the accumulation of data, and it is anticipated that the early part of 1948 will see the commencement of overall planning based on the data accumulated by that time.

The pursuance of this survey is based on the realization that up to the present a large part of the water resources of our two countries in this very important river basin are not being utilized. With effective control and regulation it will be possible to develop additional electrical power, to irrigate and make productive lands now arid, to reclaim lands now subject to flooding, to eliminate flood damage and in many other ways to increase the prosperity and well-being of the residents of the Columbia River Basin and adjacent areas on both sides of the International Boundary.

Dominion Water and Power Bureau,
Vancouver, British Columbia,
Canada

(Manuscript received July 21, 1947; presented at the Regional Meeting, Portland, Oregon, April 23, 1947; open for formal discussion until September 1, 1948.)

DISCUSSION OF "THE BACKWATER CURVE" By H. PUTMAN

[Trans., v. 27, pp. 860-862, 1946]

C. I. Posey (Iowa Institute of Hydraulic Research, Iowa City, Iowa)--The author's graphical construction is interesting. It has the usual advantages of graphical methods, easy detection of gross errors and of situations where extra care is necessary to obtain accurate results. It also offers special advantages if curves must be computed for several different discharges or slopes. The special ease with which slope changes may be taken into account should make the method particularly useful for flow-profile analyses.

The author's method of integration by fitting a parabola through equidistant ordinates is not so appealing. The limits of integration in practical problems are seldom whole numbers, so that the equidistant ordinates would occur at values of the depth which would contain fractions and thus be awkward to compute. Moreover, the shape of the backwater curve is poorly approximated by parabolas, even of higher degree than the fourth. The writer's preference in integrating is to use a sufficiently large number of ordinates that the trapezoidal rule will yield accurate results. By plotting the curve to be integrated on coordinate paper (with as many points as seems desirable to establish the shape of the curve) and using a close spacing of ordinates, say $\Delta y = 0.1$, the successive ordinate values can be read off and added on a machine, the cumulative total being recorded at intervals as desired to obtain the integral curve. By this method, the shape of the backwater curve through the whole range is obtained with little, if any, more labor than for the computation of a single point by the integration formula.

A question that might well be raised in the discussion of methods of computing backwater curves is that of the proper standard of comparison. There seems to be a concensus of opionion that a method is incorrect unless it gives results that agree closely with those obtained by use of the step method, using Manning's or Kutter's formula and very short steps. If this basis of comparison is used, the writer seldom finds it necessary to use any method for computing backwater curves in uniform channels that is more complicated than Bresse's. By proper evaluation of the constants in Bresse's equation, an almost perfect fit can be obtained for even very narrow rectangular channels, and for non-rectangular channels in which the deviation from rectangular shape is not great, or in which velocity-head changes are not important. To do this, the value of the normal depth appearing in the Bresse equation should be determined by the Manning formula. Since according to Bresse, the friction slope is taken as $S_f = V^2/C^2y$ the value of C to be used should be that which will make S_f correct according to the Manning formula, or $C = 1.486\, R^{2/3}/ny^{1/2}$. Similarly, for non-rectangular channels $C = 1.486\, AR^{2/3}/n\, Ty^{3/2}$. A is the area and T the surface width. Experience shows that values of C so computed will be nearly the same at each end of the reach. An appropriate intermediate value is selected for use in Bresse's formula, which will then give results agreeing very closely with the step method except in the close neighborhood of the critical depth, and except for non-rectangular channels in which velocity-head changes have an important effect which cannot be successfully approximated by assuming the section to be rectangular.

In view of the far-reaching effects of backwater curves and the economic values that may hinge upon their correct evaluation, it has seemed to the writer that a better criterion than mere agreement with the step method ought to be made available. The basic tenet of the step method, and indeed of all methods of computing backwater curves that have any claim to rationality, is that the rate of energy loss through friction at any depth, in gradually varied flow, is the same as it would be for uniform flow at that depth. Since the depths change very slowly through most of the backwater curves this might seem to be a reasonable assumption, yet, we are not justified in assuming that it must be true.

The writer knows of only a few instances where observed and computed backwater curves have been compared. Except for a set of experiments by Mononobe, these have been isolated examples from the field. Mononobe's tests were run in a flume 36 feet long. Curves up to nearly 150 feet in length were obtained by superposition. In an effort to extend the range of controlled backwater experiments, tests were run in 1945 and 1946 by Hsu-Hua Hu, using an eighty-foot tilting flume of the Iowa Institute of Hydraulic Research. The following brief description of his tests is abstracted

from his unpublished thesis "An Experimental Study of Backwater Curves," copies of which are available on loan from the Graduate College of the State University of Iowa.

Curves of the M1, M2, H2, and S1 types were obtained from successive runs in a steel flume 27 inches wide, 13 1/2 inches deep, and 80 feet long. It had been artificially roughened by dashing 20-30 mesh sand onto a freshly painted surface. Depths were read by hook gauges in eight stilling wells connected to piezometer taps at ten-foot intervals along the centerline of the flume. Discharges were measured by a calibrated elbow meter. The bottom of the flume was set to grade with maximum deviations of less than 0.01 foot.

Manning's n as determined by the depth of normal flow approached by the M1 and M2 curves at the same discharge was 0.015. For the normal flow approaching the S1 curve, it was between 0.015 and 0.016.

Fitting the successive runs together to obtain long curves (which in this investigation were as long as 1000 feet) was not an entirely satisfactory procedure, as agreement in both depths and slopes could not always be obtained. Judgment had to be used in the fitting process, but the maximum range, either way, permitted by the discrepancies did not appear to be enough to modify the following rather surprising conclusions: (1) Backwater curves, computed with Manning's n = 0.015 and taking velocity head changes into account, fitted the observed M1 and M2 curves very closely. (2) A close fit could not be similarly obtained for the H2 curve unless n was increased to 0.022. (3) A close fit could not be obtained for the S1 curve unless n was decreased to zero.

Hu's conclusions would seem to justify further experimental investigation of backwater curves. The author's graphical method will provide a most convenient way of making the computations for such an investigation.

Henri J. Putman (6 rue du Nord, Le Zoute, Belgium, Author's closure)--The backwater curve is a curve which is defined by its derivative, the equation of which is in (2): $dx/dy = f(y)$.

The error in the integral or backwater curve, made by fitting a parabola into the derivative is given by formulas which are found in the reference books such as "Formulae on numerical integration" of the Bureau of Standards, Washington D. C. The higher the degree of the parabola, the smaller the error but the more intricate the procedure.

When using the trapezoidal rule, Posey takes the first degree or straight line.

In the given example, Eq. (6), there is only one parabola of the fourth degree for the whole step corresponding to the limits ten and six feet. This procedure takes only five ordinates of the derivative which being of the fourth degree gives an integral or backwater curve assimilated to a parabola of the fifth degree.

With the trapezoidal rule, taking for instance partial increments of 0.1 ft for the abscissa, we obtain within the limits ten to six feet, 41 ordinates for the derivative curve. With our diagram, Figure 1, the curve being drawn with a scale of 1×10^{-4} to an inch for the ordinates and 1×10^{-5} for the abscissae we shall be able to read the values of $\eta = dy/dx$ with three figures, Table 3; this gives us also three figures for $\mu = dx/dy$. With the trapezoidal rule we have to add these 41 successive ordinates.

The authors's preference goes to the parabola of the third or the second degree, with this last for instance taking three successive ordinates together, we shall obtain a better approximation than with the first degree.

In practice, if the integration is performed graphically, it will soon appear that the 0.1 increment is useful only where the curvature of the derivative is the greatest. In the flatter part of the curve increments of 0.3 feet and later 0.9 feet suffice.

If the increments are taken as whole numbers, it is always possible to adjust the division of the increments in order to obtain groups of three ordinates, leaving the remaining, if any, for a parabola of the first degree.

Corrigenda--The following corrections are noted in this paper as published: (1) p. 860, next line below Eq. 3, ratio should be dy/dx instead of the inverse; (2) p. 861, Eq. 5, coefficient of μ_0 should be 7, not y; (3) p. 862, Table 2, first column should have a heading, Ft; and in right hand column, the third entry should be 15.5, not 17.5; (4) p. 862, Table 3, the headings should be 10 ft, 9 ft, etc., and "ft." should be deleted below the box heading; also "u =" should be deleted, as the values given are of η; and (5) in the eighth line from the end, beginning "If the slope...", S1 should replace S.

DISCUSSION OF "MACROTURBULENCE IN NATURAL STREAM FLOW"

By GERARD H. MATTHES

[Trans., v. 28, pp. 255-261, 1947]

B. Hellström (The Royal Institute of Technology, Stockholm, Sweden)--In Table 1 the author has listed the more important dynamic processes of macroturbulence in natural stream flow. The last type is referred to as "continuous double helicoidal flow in straight channels," the characteristics being that this movement occurs only in long straight reaches having deep rectangular or trapezoidal cross sections. GIBSON [see "References" at end of discussion, 1909] considers that the helicoidal flow is caused by the action of the sides of the channel, an opinion which is not shared by JEFFREYS [1929]. According to AHLBORN [1922] the movement is caused by vortices, formed at the bottom, when they are rising to the surface.

In 1917 the writer built a simple and somewhat crude apparatus for measuring the direction of helicoidal flow in small rivers. Two photographs of the apparatus are shown in Figure 1.

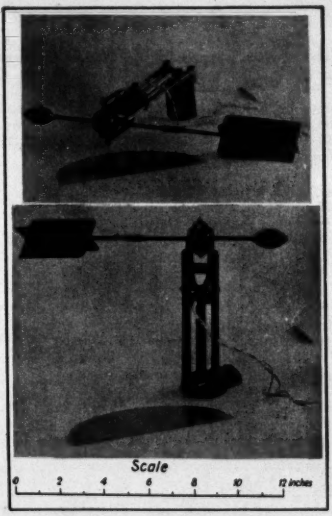

Fig. 1--Device for measuring direction of helicoidal flow

The apparatus consists of a vane balancing around a cardanic suspension. It is movable practically without friction. When the apparatus is sunk into the stream the vane places itself in the direction of the current. By loosening a spring device it is possible to fasten the vane by means of two arms which clutch and fix a ball on the axis of the vane. The apparatus, which is attached to a pipe around the vertical suspension rod, is then pulled up from the water without displacing the rod. The position of the vane is read on a graduated celluloid scale, indicating the deviations of the vane horizontally as well as vertically.

The rod is provided with a spirit-level by which the rod can be kept vertical. The zero-position of the vane in the water is made to conform exactly to the main direction of the stream by keeping a horizontal maneuvering arm, attached to the rod, at right angles to the stream. Figure 2 shows how the apparatus is fixed during measurements in a stream.

Since the vane is not placed symmetrically in relation to the suspension rod, errors may possibly arise. Such errors may, however, be compensated if the vane and its balancing counterweight are interchanged; a measurement of the direction of the current at the points in question can then be carried out with the suspension rod both on the right and on the left side of the vane. The mean value of the two readings is then considered as the correct direction of the current. Tests show, however, that the position of the vane in relation to the suspension rod does not influence the results.

The result of a measurement in a small stream is shown in Figure 3. The cross section, where the measurements were made, was chosen at the downstream end of a fairly long, even and

regular reach of the stream. The bottom material consisted of fine sand. At the time the direction of flow was measured, the average velocity of the stream, ascertained by using an ordinary

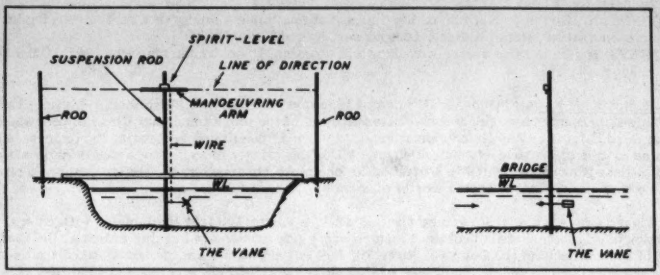

Fig. 2--Assembly of apparatus for measuring helicoidal flow

current meter was 2.3 ft/sec. The width of the stream was five feet and the depth one foot. The measurements showed that the water moved in two helicoidal flows in the manner diagrammatically shown in Figure 3. The full-drawn lines show the movement near the surface and the dotted lines the movement near the bottom. In the middle of the stream the flow is directed obliquely downwards and at the sides obliquely upwards. In the horizontal plane the greatest deviation from the main direction of the stream was seven degrees. In the vertical direction the greatest deviation was five degrees.

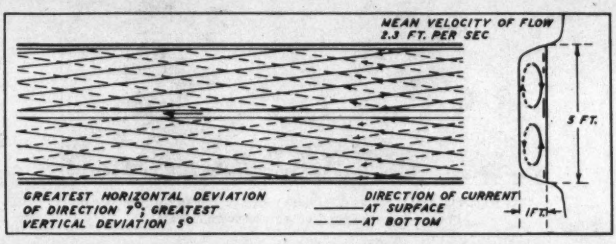

Fig. 3--Results of observations of helicoidal flow in a small stream

Similar measurements were carried out in 1918 in a rectangular wooden flume five feet by ten feet. The same phenomenon was observed, although the horizontal and vertical deviations of the stream lines were less than the figures given above.

Recently a study was made of the characteristic hydraulic figures of the flow of water in a long stretch of a flume of reinforced concrete for floating timber in the north of Sweden. The cross section of the flume was trapezoidal, the bottom width being eight inches, the depth of water two feet, and the slopes of the sides one vertical to 1.5 horizontal. The average velocity of the water varied between 3.0 and 7.2 ft/sec. In this case the investigation failed to disclose any helicoidal flow.

Hydraulic engineers should be grateful to Matthes for his valuable contribution to research work with regard to macroturbulence based on many years of studies. It will be a rich field for hydraulic engineers to examine the different types of macroturbulence listed by Matthes. This study should not be confined to natural streams only; beautiful examples of macroturbulence will be found in front of intakes of water-power stations. It is felt that the practical engineer should pay more attention to this subject in the design than is customary.

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JEFFREYS, H., On the transverse circulation in streams, Proc. Cambridge Phil. Soc., Cambridge, v. 25, p. 20, 1929.

R. Robinson Rowe (California Division of Highways, Sacramento, California)--Matthes has, in Table 1, presented a comprehensive classification of the more important dynamic processes. In the third column he has listed characteristics, such as conditions generating the processes and implied causes of the macroturbulent effect. While the variety of such processes in nature is too wide to list all characteristics in a brief table, one other observed by the writer destroyed riparian land so voraciously that it seems worthy of mention.

Figure 4 shows the first surface manifestation, a vortex 100 feet in diameter with central depression of one foot. Similar vortices formed every five minutes in regular cycles at the confluence of two channels of the Colorado River 700 feet downstream from the south end of the Needles levee (as it existed in 1939). The river was discharging 11,000 cfs in a channel 1500 feet wide at a mean velocity of about three ft/sec. The bed was a shifting sandy silt on which silts were transported fluently along the bed and sands were moving in bars by saltation.

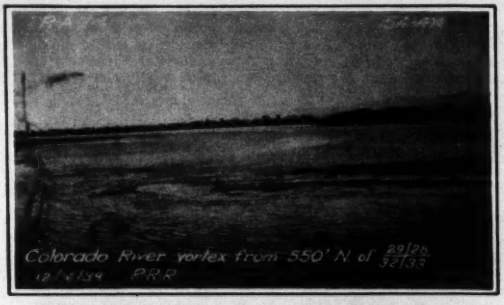

Fig. 4--Origin of eddy at confluence of two channels, just as it breaks the surface and starts downstream

During the formation of the vortex, the surface appeared to decelerate from a steady three ft/sec to a negligible velocity, and ripples were replaced by a glassy slick. Then the vortex, which had formed below, broke the surface with an audible swish and started moving downstream slowly. As if backed up by development of the vortex, a turbulent current followed the moving eddy and seemed to push it along until it developed a velocity of about five ft/sec.

Figure 5 shows the eddy and its slick approaching the right bank of the river 1400 feet downstream from the origin of the vortex. Rotation is still strong and the outer elements of the eddy combine velocities of rotation and translation to attack the bank with a local velocity of about seven ft/sec. In this view, looking downstream, the turbulence in the background was caused by the preceding eddy. The bank at this point had retreated 520 feet as a result of this process in a fairly short time. The land lost is indicated by the headland at the downstream end of the embayment.

Figure 6 shows the composite velocity at work, 2000 feet downstream from the origin of the vortex. The rotational motion has been dissipated, leaving a swift current at the bank and slack water off shore. This is rhythmic and cyclic, the swift phases being slick and quiet, (foreground) followed by a noisy tumbling surge (middle distance) and an ordinary rippling phase (background) to complete the cycle.

During the passage of the slick, banks are undercut vertically to a depth of four feet and the alluvial bottom land drops off in large bites (left center). This is not unusual in Mohave Valley, but it was astonishing to find it so active at a controlled low stage.

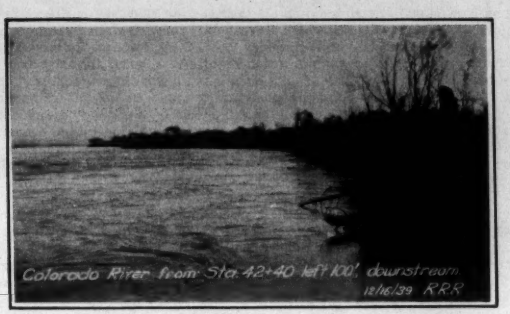

Fig. 5--Eddy with slick surface reaches right bank 1400 feet downstream from origin

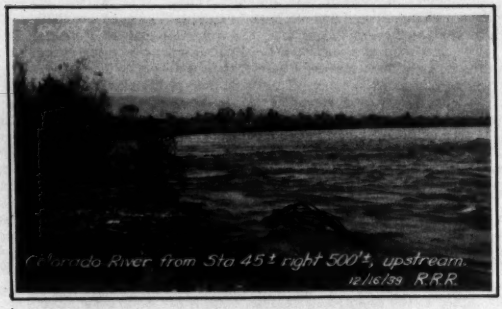

Fig. 6--Bank eroding rapidly 2000 feet downstream from origin of eddy

In attempting to classify the process according to the author's Table 1, the writer is handicapped by the fact that the Colorado River is a very turbid stream and only surface manifestations could be observed. As a hypothesis, a Class III (1) vortex was formed by kolk action over the tapering bar between two confluent channels. (The author defines this type as intermittent rather than periodic, and it is admitted that the periodicity observed could have been accidental.) After translation began, the process was Class I (3), although the characteristics are not included in the author's table. When the moving eddy reached the bank it became Class II (2), but again the particular characteristics are not tabulated. Finally, the spent eddy generated surges at Class I (1) or I (2), of diminishing magnitude as they proceeded downstream.

The phenomenon has been described in detail to emphasize the extent of erosion from macroturbulent processes at low velocity and stage. In practice, such erosion cannot be controlled by regulation of discharge. In fact, the very regulation of discharge may be responsible, in this case, for the development of cyclic turbulence.

Gerard H. Matthes (Broadway Central Hotel, New York, New York, Author's closure)--The discussions of this paper strike responsive notes which are most gratifying. Hellström's apparatus for measuring the obliquity of flow, horizontally as well as vertically, in a channel with double helicoidal flow, should be of particular interest, foreshadowing as it does the possibilities of developing similar apparatus on a larger scale for determining subsurface flow directions accurately in large rivers. Present-day devices for making determinations of this kind are not sufficiently sensitive and dependable to yield results of scientific value.

In his closing remarks, Hellström points out the need for research in macroturbulence phenomena at structures. This is a field in which a great deal remains to be accomplished. Assisted by his students at the Royal Institute of Technology, Stockholm, Sweden, Hellström, for some years has been investigating the motion of water in front of outlets in dams, and intakes of penstocks. In the past, loss of head at such points has usually been taken much for granted. As a result, the mechanics of flow have remained much in need of clarification. By way of example of what can be accomplished by "streamlining" approach velocities, should be mentioned the nine-foot diameter steel spillway siphons on the St. Francis River, Arkansas, built by the United States Army Engineers [ANDREWS, 1940]. The resulting coefficients of efficiency for one of these siphons, as determined by carefully conducted tests, showed 97.0 per cent as against the previously established value of 75 per cent, and 20 per cent more than the design value.

Research is at present being planned in the United States into the macroturbulence mechanics of what commonly goes by the name of "underscour," which annually destroys hundreds of bridges through the undermining of piers and abutments. The practical difficulties that stand in the way of conducting observations, both in the field and in the laboratory, have left these underscour phenomena cloaked in obscurity. These difficulties appear to attach to many macroturbulence phenomena involving helicoidal or vortex flows.

Rowe's observations, made at the confluence of two channels of the Colorado River, with accompanying photographs, are precisely the class of information needed to further macroturbulence research. The surges are of Type I (3), characteristic of sudden changes in flow direction such as occur at confluences of streams. As stated in Table 1 of the author's paper, surges of this type are accompanied by eddying and at times by reversal of rotation. The vortex, 100 feet in diameter, with central depression of one foot, was a suction eddy of Type II (2). The slick which preceded it was produced by a vortex of the "kolk" type; the water raised to the surface by the kolk produced the boil. It should be explained that in a water surface covered by ripples a boil always presents a glassy or slick surface. This is caused by the rapidly up-welling water which creates a surface immune to ordinary wind effects. In the case described by Rowe the kolk action indicated by the slick caused the deepening, which in turn caused the bank to cave. As stated in Table 1 under III (1) the bed deepening in such case is rapid. Practically all high-water bank caving along alluvial rivers is of this kind, the action always being local and highly concentrated, resulting in so-called "pocket caving." When the kolk action transplants itself downstream, as witnessed by Rowe, the pocket caving repeats at intervals, the general effect on the bank being one of "large bites" being taken out of it as stated by him. Bank caving of this type must not be confused with low-water bank caving, which latter is a slow but steady attritional process, devoid of kolk action, and which extends more or less continuously along an appreciable stretch of bank. Rowe's classification of the successive phases of the macroturbulence exhibit which he saw are well stated. In his last paragraph he points out correctly that the erosional processes that were involved cannot be controlled by regulation of discharge. His discussion, as a whole, confirms the findings of the author to the effect, that velocity of flow (which in a sense is symbolic of discharge) is not the controlling factor that promotes macroturbulence of the vortex type. This has been found to be true also of the vortices which produce underscour at bridge piers. It is the angle made by one current with another current or with a structure such as a bridge pier, that is the primary cause.

The discussion submitted by François E. Matthes reflects the exhaustive studies which he has made in the gorge of the Potomac over a period of years, in his leisure moments. The pebbles described by him as wedged in cracks in the rock promontory, are of interest in still another way, to which the author's attention was directed by F. E. Matthes during a visit with him to the site, namely, they are so situated that it is evident that they did not drop into their present positions but were driven upward into them. This is further proof of the energy in the rising currents along the upstream face of the cliff, which entrained the pebbles. F. E. Matthes concludes that once jammed in place, the pebbles doubtless have become tightly wedged by alternating contraction and expansion of the rock masses caused by temperature changes. In this connection he referred to a study by WENTWORTH [1911] who ably explained this phenomenon based on his own observations in the gorge of the Potomac.

Observations of the kind made by F. E. Matthes, and also those made by Rowe, are examples worth following by hydrologists and engineers concerned with river problems. What, probably, more than any other obstacle to the study of dynamics of streams, has made progress in this field slow, is man's involuntary habit of permitting his eye to be intrigued by surface flow phenomena without being able to correlate these with the subsurface phenomena that produce them. Since stream flow performs nearly all of its work at the bed and at the submerged parts of banks, at a time when turbidity is greatest and becomes an impenetrable screen, the best starting point for

the student is to study dry stream beds. Much can be learned from a dry, or nearly dry meadow brook which permits of close examination. When flow resumes in it, the macroturbulence phenomena which present themselves at the surface can then be correlated with what is happening at the stream bed. The study of the Potomac River, discussed by F. E. Matthes, is an excellent illustration of the logic of this approach to the study of stream dynamics. The presence of water-worn boulders, nine to fifteen inches in diameter deposited at high points on the cliff, described by him, and of freshly worn pot holes in this cliff more than half way up on its downstream side, are plain evidences of the magnitude of the macroturbulence action that works during high stages. These cannot be evaluated by looking at the river when at a high stage. Mere surface velocities, however impressive to the eye, reveal little except to the well-informed, and mean velocity in the cross section becomes an imaginary quantity that finds no application in such studies.

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DISCUSSION OF "A DETERMINATION OF THE EFFECT OF TOPOGRAPHY UPON PRECIPITATION" by WILLIAM C. SPREEN

[Trans., v. 28, pp. 285-290, 1947]

Walter T. Wilson (44 Loma Road, Redwood City, California)--A difficult and subtle feature of the studies presented by Spreen is the high correlation sometimes existing between various topographic parameters which are regarded as the independent, so-called variables. An example is the correlation between elevation and slope or roughness of terrain. Except in plateau regions this correlation may be high, and it is difficult to assign proper physical causes to particular parameters.

As storms pass over rugged terrain, which takes its toll of orographic precipitation, the air masses experience depletion of precipitable water, and subsequent precipitation from the same air masses as they subsequently reach higher peaks may be less than the precipitation occurring at lower elevations, but nearer the moisture source. This suggests experimentation with additional parameters. The diminution of precipitable water content with increased elevation is well known, and appears to render paradoxical the observed increase of precipitation with increased elevation. Conversely, however, the frequency distribution of the height of the condensation level appears to favor more frequent precipitation at higher elevations.

In selecting an appropriate scale for the topographic parameters, one of the elements to consider is the scale of the topography itself. Another factor is the spacing of observation stations. A third factor, which may remain as a source of residual error, is the small-scale effect of local exposure. A linear dimension of this factor is the radius within which the station may have been moved without adequate record of its exposure.

A fact to be emphasized in a problem such as this, is the great importance of sampling the range of each parameter; and, where they operate jointly, the combinations should be sampled. For adequate replication, the number of stations required is indicated by the product of the number of classes of each parameter. With eight orientation classes, four for elevation, four for roughness or slope, and four for exposure, the product is 512 stations. Of course some of the theoretical combinations of variables will not exist in nature, but the number of stations required is still great. A mitigating feature of this requirement is the conservative nature of some of the relations over wide areas, permitting transfer of knowledge from one region to another.

Associated with this aspect of the problem is the fact that, of necessity, stations have been located where people live, thus strongly biasing the sample in the direction of valley and other sheltered locations. A solution would be the establishment of seasonal precipitation gages at isolated sites deliberately chosen to sample the parameters which are becoming identified by studies such as Spreen's.

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NOTES AND PERSONALIA

NOTES

Plans for the Eighth General Assembly, International Union of Geodesy and Geophysics--From England and Norway comes word that plans for the Eighth General Assembly, IUGG to be held in Oslo, Norway, August 19 to 28, 1948, are progressing well. Programs are now about complete, and advance registration indicates excellent world-wide attendance. It is anticipated that between 75 and 100 delegates and guests will be in attendance from the United States. Preliminary programs will be available by late spring.

Plans for the International Geological Congress in England--From London comes word that plans are progressing well for the International Geological Congress to be held in London August 25 to September 1, 1948, with field trips preceding and following the meeting. There has been some concern about the thought on the part of Americans that many should not go because inroads should not be made on British food supplies. The Committee has sent assurance that there is no cause for canceling plans to attend the Congress on this account, and further assures that it appears likely that additional boats will be put into service by summer that will serve to ease the present shortage of passage. Sailing dates for some boats have not yet been established. The Committee is hopeful that the 500 provisional registrants from the United States will complete their arrangements to come.

Seventh Pacific Science Congress--The Royal Society of New Zealand, with the approval and support of the Government, is issuing invitations for the Seventh Pacific Congress to be held in New Zealand in February 1949. The Secretary-General of the Congress is Gilbert Archey, Auckland Institute and Museum, Aukland, New Zealand.

Meeting of American Congress on Surveying and Mapping--The Eighth Annual Meeting of the Congress on Surveying and Mapping is scheduled for July 1-3, 1948 at the Hotel Statler, Washington, D. C.

Submarine gravity expedition of the U. S. S. Argonaut--The U. S. S. Argonaut, J. P. Currie commanding, sailed from New London, Connecticut on February 23, 1948, on a 30-day expedition for the measurement of gravity at sea in the Bahama Islands region. The expedition was arranged with the cooperation of the Office of Naval Research, Navy Department, and Commander Submarine Force, U. S. Atlantic Fleet. Maurice Ewing, J. Lamar Worzel, and C. L. Drake made the scientific observations. The gravity observations were made with a Vening Meinesz pendulum apparatus and a Bell Telephone Laboratories crystal chronometer, loaned by the Woods Hole Oceanographic Institution. Additional observations of wave pressures are being made with a sensitive pressure meter loaned by the Naval Ordnance Laboratory, to observe the relationship of wave motions to the disturbances of the pendulum apparatus.

These observations continue in more detail the investigations of gravity anomalies associated with the large topographic relief of the Bahama Islands area. The profiles within the deep channels are laid approximately perpendicular to the structural trends, and observations will be made continuously on those profiles. The profiles will terminate as close to the shoal areas as safe operations permit. This work is part of a two-year program of gravity observations at sea, sponsored by the Office of Naval Research. J. Lamar Worzel is at present in charge of the project, under the direction of Maurice Ewing of Columbia University.

Earthquakes, December 1947 and January 1948--The United States Coast and Geodetic Survey, cooperating with Science Service, the Jesuit Seismological Association, and a selected group of widely scattered seismograph stations, has located provisional epicenters during this period as shown in Table 1.

The following note on the earthquake of December 15, 1947 has been supplied by Ross R. Heinrich of St. Louis University.

The earthquake which occurred on December 15, 1947 during the 19th hour U. T. in the south Pacific Ocean furnishes some interesting seismic data. This earthquake gives an answer to a question put forth by B. Gutenberg and C. F. Richter in their comprehensive reports on the "Seismicity of the Earth."

In their first paper, (Geological Society of America, Special Paper 34, 131 pp., August 1941) speaking of the Circum-Pacific seismic belt they state (p. 24), "The active belt returns eastward

Table 1--Provisional epicenters of the United States Coast and Geodetic Survey

Date	Time U. T.	Epicenter Lat.		Epicenter Long.		Remarks
1947	h m	°		°		
Dec. 14	2 16.2	26	S	63	W	North central Argentina; depth 100 km
Dec. 15	19 20.5	59	S	161	W	About 2000 miles south of New Zealand; depth 100 km
Dec. 16	11 26.7	30	N	114	W	Gulf of California
Dec. 24	16 36.7	16	N	98	W	Near Coast of Oaxaca, Mexico
	17 36.5					
Dec. 26	16 43.8	20	S	168	E	New Hebrides Islands
Dec. 30	1 55.3	9.5	N	84.5	W	Near coast of Costa Rica
Dec. 31	15 06.5	15	S	176	W	Samoan region
1948						
Jan. 4	8 56.5	21	S	180		Tonga Island region; depth 600 km; magnitude[a] 7
Jan. 6	17 23.4	16.5	N	98	W	Oaxaca, Mexico; magnitude[a] 7
Jan. 10	5 14.5	20	S	169	E	New Hebrides Islands region
Jan. 12	2 25.4	10	S	109	W	1200 miles north of Easter Island
Jan. 16	11 08.5	52	N	172	E	Aleutian Islands; depth 100 km; magnitude[a] 6 3/4
Jan. 17	7 11.3	15	N	147	E	Mariana Islands region; depth 100 km; magnitude[a] 6 1/2
Jan. 20	9 44.0	33	S	179	E	Kermadec Islands region, slightly deeper than normal
Jan. 21	18 04.1	11	N	66	W	Off coast Venezuela; magnitude[a] 7
Jan. 22	12 55.3	22	S	175	W	Tonga Islands region; depth 150 km, magnitude[a] 7
Jan. 24	17 46.6	10	N	122	E	Off southwest coast of Panay, P. I., 17 reported dead, at least $1,500,000 property damage; magnitude[a] 8 1/4
Jan. 24	23 08.1	19	N	108	W	Central Mexico
Jan. 26	14 10.8	10	N	122	E	Aftershock of earthquake of Jan. 24, $17^h46.6^m$
Jan. 26	17 54.0	54	N	164	W	Aleutian Islands region
Jan. 27	11 58.3	20	S	178	W	Tonga Island region; depth 600 km; magnitude[a] 7 1/4
Jan. 28	3 47.2	10	N	122	E	Aftershock of earthquake of Jan. 24, $17^h46.6^m$
Jan. 3	2 57.7	28	S	113	W	Easter Island region

[a]Magnitudes reported by Pasadena.

on the south limb of the Macquarie Island loop, beyond which no epicenters are available to trace it. It may connect along the Easter Island Rise with the branch off South America." Later (p. 38) they note, "There is unfortunately no seismic evidence bearing on the moot question of a structure connecting the South Antillean arc across Antarctica with New Zealand. Recent teleseismic observations provide no data indicating shocks either on the Antarctic continent itself, or in any more northerly locality that might fall in the gap..."

In the supplementary paper by the same authors (Geological Society of America Bulletin, v. 56, pp. 603-667, 1945), we find the following (p. 657), "Present information suggests describing as a unit the seismicity of a belt which extends southward from Oaxaca in Mexico, passes west of the Galapagos Islands along the Easter Island Ridge into the Antarctic Pacific and thence apparently continues along the Antarctic-Indian Swell south and southwest of the Macquarie Islands... No intermediate (60 to 300 km) or deep (greater than 300 km) shocks are associated with the belt... No shocks are known along the Ridge or its continuation between longitudes 152 W and 160 E, so that drawing of an active belt across this interval is hypothetical."

For the earthquake of December 15, 1947, the United States Coast and Geodetic Survey has assigned a provisional epicenter of 59° S, 161° W; origin time $19^h20.5^m$ U. T.; depth of focus 100 km. In making a preliminary determination for the Jesuit Seismological Association, I found that there is some question of the longitudinal shift of the epicenter with the data now (January 10, 1948) available. I selected a tentative location of 60.3 S, 166.8 W; origin time $19^h20^m17^s$; depth of focus 100 km. In both of these determinations the nearest station was the expeditionary station on Antarctica. A better fix will be possible when data from New Zealand and Australian stations are available. It seems however that the epicenter of the earthquake of December 15, 1947 will fall within the gap of data cited by Gutenberg and Richter (end of comment by R. R. Heinrich).

The following information on the Philippine Islands earthquake of January 24, 1948 was furnished by Frank Neumann of the United States Coast and Geodetic Survey. The islands of Negros, Cabu, Leyte and Marinduque were the hardest hit. Approximately 200 houses were destroyed. The damage to church properties alone has been estimated at $3,500,000. Fifteen churches were damaged or destroyed. There was severe damage at Antique and Iloilo where the intensity was 8 to 8 1/2

R. F. Falling of debris from buildings caused the greatest number of casualties. Two fishermen were reported drowned in a tidal wave sweeping Iloilo Strait but tide gauges at other points recorded no wave. The beach 13 miles west of Iloilo has been reported to have sunk ten feet. It was the most severe quake in the Islands since 1923.

Woods Hole vessels active--The Balanus left Woods Hole in February 1948, for the first of four seasonal one-month surveys of the area off New York City. Eugene Mysona is captain of the vessel, while the scientific party includes William L. Ford, Bostwick H. Ketchum, and Carlyle Hayes. Newly equipped with radar and gyro compass, the auxiliary ketch Atlantis of the Woods Hole Oceanographic Institution sailed from Woods Hole on December 10, 1947, for an extended oceanographic cruise of the eastern Atlantic. Martin J. Pollak is in charge of the scientific party. The Atlantis arrived at Malta on January 16, 1948 en route to the Piraeus. She is due to return to the United States in June. The Caryn has been assigned to the Bermuda Biological Station. She is scheduled to conduct deep-sea dredging off Bermuda in June under Loren P. Woods and Fritz Haas of the Chicago Natural History Museum.

Advisory Committee on Geophysics, Office of Naval Research--On the request of the Office of Naval Research, the National Research Council has appointed an advisory committee on geophysics to aid the ONR on objectives established as follows: (1) To foster, in cooperation with other agencies, geological, geographical, and geophysical explorations of little known areas of the Earth such as the islands of the Western Pacific and the Arctic and Antarctic. Such exploration may include all aspects of the natural evironment and problems of human and economic geography and ethnography as well as the more limited objectives implied in the terms geology and geophysics. (2) To conduct laboratory and field studies leading to a greater understanding of the properties and processes existing in the outer hundred kilometers of the Earth's crust. (3) To develop instruments and techniques for determination of the Earth's properties; for example, universal airborne magnetometer equipment.

The committee membership is as follows: Walter H. Newhouse, Chairman; Harry H. Hess, Vice Chairman; Roland F. Beers; Maurice Ewing; Ellis A. Johnson; Lester E. Klimm; William C. Krumbein; William W. Rubey, and J. Frank Schairer, with R. C. Gibbs, Chairman of the Division of Mathematical and Physical Sciences, NRC, and Arthur Bevan, Chairman of the Division of Geology and Geography, NRC, as collaborating administrative advisers.

Swedish Deep-Sea Oceanographic Expedition reaches Hawaii--The Albatross, under Hans Pettersson, was in port at Honolulu from November 28 to December 12, 1947, having previously called at the Galapagos Islands and Tahiti. From Honolulu the expedition will go to Kusaie, Ponape, and the Netherlands East Indies.

Conference on Ocean-Surface Waves--A conference on ocean-surface waves was held by the New York Academy of Sciences at the American Museum of Natural History on March 18 and 19, 1948.

Ronne Antarctic Expedition--The expedition vessel, City of Beaumont, was broken out from the bay ice in Neny Fjord, Palmer Peninsula, by the icebreakers of U. S. Navy Task Force 39, and sailed for home on February 22, 1948. The Finn Ronne Expedition conducted geophysical research in the region for a year, basing in the former United States Antarctic Service East Base at Stonington Island.

Study of the solar eclipse on May 8-9, 1948-- Field parties, under the sponsorship of the National Geographic Society, are being sent to seven stations ranging from Burma to the Aleutian Islands for studies of the partial solar eclipse to occur May 8-9, 1948. Astronomers and geodetic engineers from various universities and government agencies are cooperating in the project. This expedition will attempt to establish more accurately the shape and figure of the Earth and to tie together the triangulation networks of the various countries in which the stations are located.

Resumption of publication of oceanographic journal--After a suspension of six years, the Conseil Permanent International pour l'Exploration de la Mer has resumed publication of its Journal. Volume 15, Number 1, dated July 1947, was received in the United States in January 1948. Orders for copies should be sent to Messrs. Andr. Fred Hϕst and Sϕn, Bredgade, Copenhagen, Denmark. The editorial address is Editor, Journal du Conseil, Fisheries Laboratory, Lowestoft, England.

The exhaustive current bibliography of oceanographic and fisheries work in the area of interest to the Council is continued. There are 28 pages of bibliography in the July 1947 issue. Subscribers,

on request, may receive reprints of this printed on one side of the page only, for use in making up card indices.

Publication of a new electronic bibliography--Volume 1, numbers 1 to 4 of Elektronentechnische Berichte have recently arrived in this country from Vienna. This is prepared under the editorship of Volker Fritsch. Numbers 1 to 3 are combined, giving in a foreword, the objectives of the publication and the various systems of classification used. Number 4 gives somewhat further information on classification, and contains 200 summary entries on 50 pages. These may be separated and used as file cards. Persons interested in subscribing should write Manzsche Verlagsbuchhandlung, Kohlmarkt 16, Vienna I, Austria.

Two new publications in Geophysics--Announcment has been made of the initiation of the publication of Archiv für Meteorologie, Geophysik, und Bioklimatologie to be published in two series: A, Meteorology and Geophysics; and B, General and Biological Climatology. These will be published separately at irregular dates and may be subscribed to independently. The first numbers will appear some time in late spring of 1948. Papers are solicited. The editors are W. Mörikofer, Physikolisch-Meteorologisches Observatorium, Davos-Platz, Switzerland; and F. Steinhauser, Zentralanstalt für Meteorologie und Geodynamik, Schlossgasse 14, Vienna V, Austria. The publisher is Springer-Verlag, Mölkerbastei 5, Vienna I, Austria.

Tide and tidal stream observations--The International Hydrographic Bureau has issued a circular letter to its member nations listing the areas from which tide data are desired. These include the Arctic, Eastern Siberia, China, Africa, Solomon Islands, Magellan Straits, and the Antarctic. Observational series for 15-day or 29-day periods are needed from as many places as possible, with at least one 12-month series in each area. In few areas of the world are tidal currents adequately covered, and results of observations, wherever obtained, are welcomed.

University of Washington Summer Oceanographic Session--The Friday Harbor Field Laboratories will offer courses in botany, chemistry, meteorology, microbiology, oceanography, physics, zoology, and physiology, between June 28 and August 21, 1948. Lectures will be given by Victor B. Scheffer and Frederick A. Zeusler in addition to the staff of the Oceanographic Laboratories.

New Antarctic exploration vessel--The Falkland Islands Dependencies Survey has acquired an American-built wooden-hull net tender of the same class as the U. S. S. Whitewood. Renamed John Biscoe after the discoverer of the southern part of the Palmer Peninsula, the 1015-ton vessel left London for Antarctica on December 18, 1947. She will carry a party of scientists under the leadership of V. E. Fuchs to replace about half the personnel now occupying seven observation stations on the Palmer Peninsula and neighboring islands.

Cosmic Ray Conference in Poland--An international conference on cosmic rays was held in Krakow, Poland, October 6 to 11, 1947. This was called by the Cosmic Ray Commission of the International Union of Physics and was supported by a grant from UNESCO. The Polish Government and the University of Krakow sponsored the meeting which was held in nine sessions. Fifteen papers were presented. Twelve countries, including the United States, were represented.

Mapping work accomplished during 1947--The United States Geological Survey has issued a 23-page mimeographed report outlining the progress on various aspects of mapping and map catologing during 1947. Copies may be secured by writing to Map Information Office, U. S. Geological Survey, Washington 25, D. C.

PERSONALIA

John N. Adkins, Assistant Professor of Geophysics, Massachusetts Institute of Technology is on leave of absence to serve as acting Head of the Geophysics Branch, Office of Naval Research.

Edward G. Bullard of Cambridge, England, will become Head of the Department of Physics at the University of Toronto in July 1948. He succeeds E. F. Burton who will become Research Professor of Physics.

G. E. R. Deacon of the Admiralty Research Laboratory, Teddington, England, attended the Wave Conference of the New York Academy of Sciences in March 1948.

C. Hewitt Dix has been named Associate Professor in the Division of Geological Sciences, California Institue of Technology, effective January 1, 1948, and will specialize in the seismic

and gravitational phases of applied geophysics. Previously he had been with the United Geophysical Company on geophysical exploration work.

Carl Eckart has been appointed Director of the Scripps Institution of Oceanography of the University of California. He was formerly Director of the Marine Physical Laboratory of the University.

H. A. Einstein has been appointed Associate Professor of Mechanical Engineering, University of California at Berkeley. He was formerly engaged in research work for the Soil Conservation Service at Pasadena.

Gordon M. Fair, Dean of the Graduate School of Engineering, Harvard University, has been awarded the Diploma of the British Institution of Water Engineers for his paper "Hydraulic Investigations of Water Distribution Systems." This is the first such award to an American citizen.

Beno Gutenberg has recently been elected an Honorary Member of the Finnish Geographical Society.

Gail A. Hathaway, Special Assistant to the Chief of Engineers, U. S. Army, has been named Chairman of the United States National Committee of the International Commission on Large Dams to succeed Michael W. Straus of the Bureau of Reclamation. The Commission will hold its first Post-War meeting in Stockholm in June 1947, and is laying plans for its next meeting which will probably be held in India in 1950.

Benjamin G. Holzman, Colonel in the Air Weather Service of the Air Forces, has been awarded the Robert M. Losey Award for outstanding contributions to the field of aeronautical meteorology during 1947.

Anders Kvale has been appointed Visiting Associate Professor of Geology of the University of California at Los Angeles. From 1939 to 1942, Professor Kvale was Chairman of the Department of Geology at Bergens Museum, Bergen, Norway.

Walter D. Lambert, President of the International Association of Geodesy, IUGG, has been recalled to active duty by the U. S. Coast and Geodetic Survey for assignment in the Washington Office.

Walter C. Lowdermilk, Past President of the American Geophysical Union, is now in North Africa on consultation with authorities of the Government with regard to conservation and water use problems. Enroute, he stopped in England. He plans to spend the summer in France and Switzerland, and to be in attendance at the General Assembly of the IUGG in Norway in August.

Alfred C. Redfield of Woods Hole Oceanographic Institution has been appointed Walker-Ames Professor at the University of Washington for the 1948 summer session.

Marvin Rice, formerly of the Hydrographic Office, U. S. Navy, has been appointed to command the new Fish and Wildlife Service vessel Albatross III.

R. Dana Russell has been appointed visiting Professor in the Division of Geological Sciences, California Institute of Technology, working especially in the field of sedimentary petrology. He is Consulting Geophysisist for the Electronics Laboratory of the U. S. Navy.

S. L. Seaton, who for a number of years had charge of the geomagnetic work in Alaska carried on by the Department of Terrestrial Magnetism, Carnegie Institution of Washington in cooperation with the University of Alaska, has been appointed Director of the Geophysical Observatory, University of Alaska. The Observatory has been reorganized with a formal unit for basic studies in Arctic geophysics, and its facilities, as they become available, will be used to develop a graduate school for the study of problems in geophysics, especially those peculiar to the Arctic.

Henry Stommel returned to Woods Hole in January 1948 after four months at the Imperial College of Science and Technology in London, where he worked on the problem of a numerical theory of ocean tides.

H. U. Sverdrup visited Honolulu in November 1947 to advise the University of Hawaii upon a program of oceanographic investigation to be undertaken at the new Hawaii Marine Laboratory at

Kaneohe Bay, the buildings for which are expected to be ready for use during the latter part of 1948. Dr. Sverdrup left Scripps Institution of Oceanography late in February 1948 to return to Norway where he has been appointed Director of the Norwegian Polar Institute, Oslo, Norway.

H. U. Sverdrup and R. H. Fleming are the authors of the articles "Indian Ocean" and "Atlantic Ocean" in the 1947 edition of the Encyclopedia Britannica.

Kendall Eugene Born, Assistant Professor of Geology, Missouri School of Mines, died in St. Louis, Missouri, September 21, 1947, two weeks after a severe abdominal operation. He was born at Chester, Illinois, February 15, 1908, received his baccalaureate degree from McKendree College in 1930, and the degree of Master of Science from Vanderbilt University in 1931. He was a teaching fellow at Vanderbilt from 1930 to 1932, and graduate Assistant at Washington University from 1932 to 1935. From 1935 to 1946 he was with the Tennessee Division of Geodesy, rising to the position of Assistant State Geologist. It was from this work that he went to the Missouri School of Mines.

Frank Leroy Flynt, in charge of the Hydraulic Branch of the Engineering Division of the Rock Island District of the Corps of Engineers, died September 10, 1947. He was born at Plattsburg, Missouri, September 4, 1885, and received his baccalaureate degree from Missouri School of Mines in 1910. He began his professional carreer with the Atlanta, Birmingham, and Atlantic Railway, and worked on the engineering staff at various railways from 1910 to 1924. Most of the period from 1924 to 1936 he worked in the St. Louis vicinity on sewer designs for St. Louis and vicinity. From that year until his death he was with the Rock Island District of the Corps of Engineers.

Clyde Philip Parkinson, engineer with Jones and Henry, Consulting Engineers of Toledo, Ohio, died May 3, 1947. He was born at Mellott, Indiana, December 12, 1910, and received his baccalaureate degree in Civil Engineering from Purdue University in 1932, and pursued graduate work for another year. He began his professional work as Camp Engineer on Emergency Conservation Work in 1933, continuing until 1935. The following year he was a project engineer on bridges for the Indiana Highway Commission. From 1936 to 1946 he was engaged on work of the Water Resources Branch of the U. S. Geological Survey at various stations in the eastern half of the country. He joined the firm of Jones and Henry in 1946.

Frederick B. Plummer of the Bureau of Economic Geology, University of Texas, died February 17, 1947. Professor Plummer was born August 31, 1886 at Hanover, New Hampshire, received a baccalaureate degree from Dartmouth in 1909, and pursued advanced studies at Chicago University in 1910 and 1911. Since that time his professional career was devoted to petroleum geology, exploration geophysics, and the teaching of geology. He became professor of petroleum engineering at the University of Texas in 1928.

Luther Crocker Snider, Professor of Geology, University of Texas, died of a heart attack May 27, 1947. He was born at Mt. Summit, Indiana, September 13, 1882, and received his baccalaureate and masters degrees from Indiana University in 1908 and 1909, respectively. He received his doctorate degree from the University of Chicago in 1915. His professional career began in 1909 with the Oklahoma Geological Survey where he continued to work until 1915, rising to the post of Assistant Director. During the ensuing period until 1940, he served as Chief Geologist of Cities Service, and as a consultant for various petroleum companies. In 1941, he became Professor of Geology at the University of Texas.

Benjamin Allen Wooten, Head of the Physics Department at the University of Alabama, died July 9, 1947. He was born at Jefferson, Alabama, July 29, 1891 and received his baccalaureate degree from Alabama Polytechnic Institute in 1911, following which he secured his masters and doctorate degrees from Columbia University in 1915 and 1917, respectively. His teaching career began at Alabama Polytechnic Institute in 1912, and in the period to 1921, he continued this association, except for the period 1917 to 1919 during which he taught at City College of New York. From 1922 to 1928, he was head of the Physics Department at Washington and Lee University, and in 1928 he became Head of the Physics Department at Alabama University.

Arthur Appleton Young, Irrigation Engineer with the United States Soil Conservation Service, died July 8, 1947. Mr. Young was born in Minniapolis, Minnesota, July 17, 1879. He graduated from Washington State College in 1904, and began his professional career as locating engineer for the Canadian Pacific Railway, but in 1907 left that work and in the ensuing 20 years, gained wide experience in irrigation, drainage, and water supply in the Pacific Northwest. In 1926 he became an irrigation engineer with the U. S. Department of Agriculture, which work he pursued until his death.

UNION, SECTION, AND COMMITTE ACTIVITIES

UNION ACTIVITIES

Pacific Coast Meeting, February 13-14, 1948

In accordance with the announced plans, the Twenty-Second Regional Meeting of the Union was held in the Engineering Building, University of California, Berkeley, California, February 13 and 14, 1948. On the morning of February 13, a meeting was held on Oceanography, and a combined one on Hydrology and Meteorology. In the afternoon, there were separate sessions in Hydrology and Meteorology. In the late afternoon, a visit was made to the 184-inch cyclotron of the University. On the morning of February 14, there were two sessions, one on Oceanography and Meteorology, and one on Hydrology. Thirty-one papers were presented, many of which will be published in subsequent issues of the Transactions. Formal registration included 149 names; the sessions were well attended.

Fred C. Scobey was Chairman of the joint session on Hydrology and Meteorology on the morning of February 13 at which six papers were presented. O. W. Swainson was Chairman of the session on Oceanography at that same time. At the afternoon session on Meteorology, R. C. Counts, Jr. was Chairman, and at the session on Hydrology, Charles H. Lee was Chairman. G. F. McEwen was Chairman of the session on Oceanography on February 14, and Walter W. Weir was Chairman of the session on Hydrology. G. F. McEwen was the General Chairman on the arranging of the meeting with J. W. Johnson in charge of local arrangements. Especially active in working out the arrangements for Hydrology was F. J. Viehmeyer, and for Meteorology were Woodrow C. Jacobs, and Lyle B. Rasey.

Representative to Sesquicentennial Celebration of the Founding of the University of Louisville

Lucien Beckner was designated as the representative of the American Geophysical Union at the Sesquicentennial Celebration of the Founding of the University of Louisville on February 9 and 10, 1948.

SECTION ACTIVITIES

SECTION OF HYDROLOGY

Minutes of the Seventh Meeting of the Washington Group--The seventh meeting of the Washington Group, Section of Hydrology was held on January 30, 1948 at the South Building, U. S. Department of Agriculture. The speaker of the evening was E. N. Munns on "Problems in Forest Hydrology."

Forest hydrology, as a phase of the broader field involves essentially the same difficulties of measurement and interpretation. This applies to flow and precipitation as well as to determinations of the functions of soil and vegetation in the water cycle. Stream flow and precipitation data are too often utilized and conclusions derived without inquiry into the reliability of the original measurements. We have still to reproduce the synthetic hydrograph to dispose adequately of rainfall by infiltration, percolation, and surface and subsurface runoff. We have yet to develop a thoroughly acceptable theory of infiltration and the techniques and equipment for translating unit values into basin infiltration. In addition, the forest hydrologist has problems of measuring the effects of forest cover and use in interception, evaporation, transpiration, and soil storage capacity. The soil question alone involves many little-understood phenomena of considerable hydrologic significance, such as the development and function of humus and soil organisms, and root structure. The forester has also to consider what types of watershed repair, including structures, and what types of management can best and most quickly achieve the desired water-control objectives. Such basic information is badly needed to answer the many questions raised by water users and recreational interests and in watershed-flood control.

Operation of the Colman soil moisture meter was demonstrated following the talk and discussion. Much interest was shown in this instrument designed by the California Experiment Station for quick determinations of soil temperature and moisture under a wide variety of conditions. The meeting adjourned at 21^h15^m.

BERNARD FRANK, Secretary

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION, JANUARY 11 TO MARCH 10, 1948

Abrams, Mr. Talbert, Abrams Aerial Survey Corp., Lansing 1, Mich. (a)
Aguerrevere, Mr. S. E., Apartado 1253, Caracas, Venezuela (abc)
Alldredge, Mr. Leroy R., 3133 Jennings Rd., Kensington, Md. (d)
Baldwin, Mr. Clarence H., 407 Maplewood Ave., Struthers, Ohio (cd)
Banerjee, Mr. B. K., 635 F St., N. W., Washington, D. C. (cg)
Barker, Mr. M. H. S., 7 Market Pl., Tebury, Glos., England (eg)
Barker, Mr. William K., 12220 Sunset Blvd., Los Angeles 26, Calif. (e)
Barnes, Mr. A. E., Lion Oil Company, P. O. Box 427, Abilene, Tex. (abd)
Bath, Mr. Gordon D., 4122 Parkside Dr., Baltimore 6, Md. (d)
Bedford, Mr. John P., Dept. of Geology, Washington University, St. Louis 5, Mo. (fgh)
Bender, Mr. Fred A., 1301 Maple St., Golden, Colo. (abcdefgh)
Black, Mr. Robert F., 410 Rosemary Lane, Falls Church, Va. (gh)
Boccalery, Mr. Michael A., 711 Edison Bldg., Los Angeles 13, Calif. (abd)
Bodhaine, Mr. G. L., 4111 N. 27th St., Tacoma 6, Wash. (g)
Bonebrake, Mr. Walter C., Atlantic Refining Co., P. O. Box 2819, Dallas, Tex. (bd)
Bossolasco, Dr. Mario, Istituto Geofisico Italiano, Piazza Leonardo da Vinci 12, Milano, Italy (abd)
Brinker, Mr. Daniel H., 329 Pleasant Valley Rd., Cleveland 9, Ohio (c)
Brown, Mr. Edwin A., 241 W. Maple Rd., Indianapolis 8, Ind. (g)
Browning, Mr. Paul F., Creole Petroleum Corp., Maracaibo, Venezuela (aeh)
Buckham, Mr. A. F., Geological Survey, Ottawa, Ont., Canada (h)
Byers, Dr. A. Roddick, Dept. of Geology, University of Saskatchewan, Saskatoon, Sask., Canada (h)
Byers, Mr. John W., McCollum Exploration Co., 853 Esperson Bldg., Houston, Tex. (b)
Cameron, Prof. H. L., 18 Prospect St., Wolfville, N. S., Canada (aefh)
Carroll, Mr. William M., 3324 N. Huson St., Tacoma, Wash. (ag)
Cathcart, Mr. Stanely H., Pennsylvania Geologic Survey, Harrisburg, Pa. (h)
Charles, Major Bernard N., Long Beach Air Force Base, Long Beach, Calif. (cde)
Coan, Mr. Grady B., P. O. Box 451, Aztec, N. M. (b)
Collins, Mr. B. W., New Zealand Geological Survey, P. O. Box 250, Timaru, New Zealand (cefg)
Constable, Mr. Guy, Creston, British Columbia, Canada (cg)
Cornell, Prof. Russel M., 2525 Colfax St., S., Minneapolis 5, Minn. (g)
Cornett, Mr. J. R., Seismograph Service Corp., P. O. Box 1590, Tulsa, Okla. (b)
Corwin, Mr. Gilbert, 607 Belmonte Park, N., Dayton 5, Ohio (fh)
Craig, Mr. Ross W., P. O. Box 1518, Lake Charles, La. (b)
Crawford, Mr. John M., 1105 S. 9th St., Ponca City, Okla. (a)
Cullings, Mr. John R., 419 N. Geyer Rd., Kirkwood 22, Mo. (cg)
Curtis, Mrs. Lydia E., 347 Madison Ave., Webster Groves 19, Mo. (c)
Dahm, Dr. Cornelius G., 3625 Bryn Mawr Dr., Dallas 5, Tex. (bdh)
Decker, Mr. LaVerne, 213 Scanlan Bldg., Houston 2, Tex. (abcdefgh)
De Jesus, Comdr. Angel G., c/o Mrs. Natividad N. de Jesus, Bureau of Civil Service, Manila, P. I. (ae)
De Blank, Mr. Bastiaan, Caribbean Petroleum Co., Apartado 19, Maracaibo, Venezuela (abh)
Dix, Prof. C. Hewitt, California Institute of Technology, Pasadena 4, Calif. (abdh)
Dodge, Mr. R. K., 613 W. Dill St., Shawnee, Okla. (ab)
Dubach, Mr. Harold W., 334 Museum of Science and Industry, 57th and Jackson Park, Chicago, Ill. (c)
Eggert, Mr. William E., 525 Rutter Ave., Kingston, Pa. (c)
Engelbrecht, Mr. Howard H., 1312 Chillum Rd., Chillum, Md. (g)
Erwin, Mr. Richard C., 2510 M St., Bakersfield, Calif. (g)
Eustis, Mr. Richard S., Jr., Lloyd Neck, Luntington, N. Y. (c)
Exner, Mr. Lawrence J., 815 Passmore St., Philadelphia 11, Pa. (c)
Fruehling, Mr. S. W., P. O. Box 1590, Tulsa 1, Okla. (b)
Galbraith, Mr. F. McIntosh, 101 Pine St., Wallace, Idaho, (abd)
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SPECIAL ANNOUNCEMENTS

Positions open on Navy Department scientific work--An urgent call has come from the Navy Department Joint Board of U. S. Civil Service Examiners, 1040 East Green Street, Pasadena 1, California for qualified scientists for professional positions as physicist, engineer (various branches), meteorologist, mathematician, statistician, and other fields of science, grades P-2 to P-8, for work at various West Coast naval research centers. Interested persons should apply directly to the Board in Pasadena, or to the Regional Director, 630 Sansome Street, San Francisco 11, California.

Atomic Energy Commission Fellowships--The National Research Council has announced a new program of fellowships, both of predoctoral grade and postdoctoral grade, for research work in the many fields of science bearing a relationship to atomic energy and its products. This program is being supported by funds provided by the Atomic Energy Commission in recognition of its responsibility for atomic energy research.

The fellowships of the postdoctoral grade will relate to three groups as follows: Physical sciences, general biological sciences, and medical sciences. In the predoctoral grade one will relate to the physical sciences and the other to the biological sciences, including basic medical science and biophysics. For information, write to the Fellowship Office, National Research Council, 2101 Constitution Avenue, Washington 25, D. C.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 29 JUNE 1948 Number 3

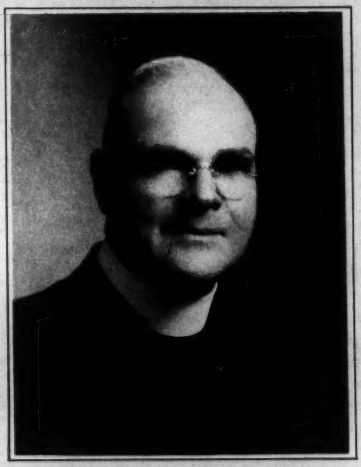
TENTH AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

Leo Otis Colbert

Mr. President: The Committee on the Award of the William Bowie Medal is happy to recommend bestowal of the William Bowie Medal on the Rev. Dr. James Bernard Macelwane, S. J., Director of the Institute of Geophysical Technology of St. Louis University.

The privilege of preparing a citation for the award of this medal to our colleague has been a pleasant task and one requiring very little effort. Father Macelwane fulfills all of the qualifications required for bestowal of this honor not only because of the success he has achieved in his chosen field of seismology but also because of his active participation in the work of several geophysical organizations in this country and abroad. One of the pioneers who helped to establish the American Geophysical Union, he has maintained an active interest through the years.



Reverend Doctor James Bernard Macelwane, S. J.
Recipient, Tenth Award of the William Bowie Medal
April 21, 1948

He has directed major projects in seismology which have materially advanced our knowledge of Earth physics and has conducted a score of minor projects which in the aggregate are equally important because of their basic potential value.

Of outstanding practical importance was his sponsorship in 1936 of a research program which demonstrated the successful use of microseismic measurements in detecting and tracking tropical hurricanes. The system of tripartite stations developed by him and his colleague, the Rev. Dr. J. Emilio Ramirez, S. J., in their research at St. Louis University was subsequently employed by the United States Navy in establishing a hurricane-warning network of stations in the West Indies.

This project, over a period of four years, has proven 100 per cent successful in detecting and tracking destructive tropical hurricanes. A similar network of stations is now being established on island bases in the western Pacific for the purpose of tracking the violent typhoons of the area.

Father Macelwane's book on Theoretical Seismology, published in 1936, reveals such a complete mastery of classical wave theory and its application to seismic-wave propagation that it serves as a final stepping stone for all who would venture into the realm of pure seismological research. His scholarly understanding of seismology and its relation to other geophysical fields, especially meteorology and geomagnetism, is revealed in more than a hundred papers and monographs. These have appeared in professional geophysical and geological publications as well as in periodicals of broader and more popular scope. His recent book entitled When the Earth Quakes attests to his deep personal desire that the layman as well as the specialist should know at least some of the mysteries of the planet on which we live.

Tenth Award of the William Bowie Medal for outstanding achievement in Geophysics; left to right, President Meinzer, Doctor Macelwane, and Admiral Colbert
(Photo by Press Association, Inc.)

Father Macelwane was primarily responsible for the reorganization in 1925 of the Jesuit Seismological Association, thereby insuring the active participation of all American Jesuit seismological stations in observational and research programs. His efforts for many years were directed toward the establishment of an Institute of Geophysical Technology at St. Louis University, and the final realization of that desire in 1944 must have been a matter of personal pride as it was a notable achievement. Certainly we owe much to him for the highly trained geophysicsts which that institution is now turning out annually.

As a member of the National Academy of Sciences and the National Research Council, as a trustee of St. Louis University, as ex-President of many scientific organizations and a member

of even more, and as a representative of this country to many international geophysical gatherings, he has made himself an integral and effective part of our effort to advance the cause of geophysical knowledge.

His success is a tribute not only to that ancient order of scholarly Jesuits, who strove for the truth in scientific as well as ecclesiastical matters, but it is also a source of profound pleasure to all of us who know him personally.

RESPONSE AND ACCEPTANCE BY JAMES B. MACELWANE

President Meinzer, Admiral Colbert, Members of the American Geophysical Union, and Friends: Most of us remember well the occasion, ten years ago, when William Bowie came forward to receive this medal which had just been created to honor him. The American Geophysical Union honored itself in honoring Bowie because his life was an extraordinary exemplification of the two things which the Union represents, research in the Earth sciences and cooperative effort in its prosecution.

I appreciate more than I can say my selection by the Committee as the recipient of this year's award of the William Bowie medal. I am grateful above measure for the testimony of the esteem of my fellow scientists embodied in Admiral Colbert's citation.

But in all sincerity I must plead that all my life long I have been at the receiving end, so to speak, of the cooperation which the medal symbolizes. Whatever I am as I stand before you I owe to the Catholic religious order to which I belong. I came to the Jesuits a country boy with only a high school education and even that received under their auspices. They gave me broad scholarly training, unusual scientific opportunities, generous support, and unfailing encouragement---the best cooperation a man ever had. In my later years I could not wish for finer scientific cooperation than I have always received from my colleagues at Saint Louis University, at the University of California, and in the wide circle of fellow scientists in the United States and abroad.

When there was question in 1925 of founding the Jesuit Seismological Association it was Harry Wood and Arthur Day who helped to bring it about. Inside that organization I have always met with most generous cooperation. In the organization of the Eastern Section of the Seismological Society of America it was Hodgson and Heck and Bailey Willis whose cooperation made it possible. Again, it was Heck and Watson Davis who joined with me in starting the three-cornered program which has worked so well for the preliminary determination of epicenters of earthquakes. I could go on indefinitely.

In this divided world with atheistic statism arrayed against Christian freedom of the individual and Western culture we need the object lesson of scientific cooperation. Western civilization stands at the crossroads today as it did when the iron curtain of Islamism was sweeping over much of Asia, Africa, and Europe, and was permanently halted at the gates of Vienna.

But the American Geophysical Union with its William Bowie Award stands for more than all this. Its motto is unselfish cooperation. Now unfailing selflessness requires a powerful motive. Sometimes it calls for heroism to conquer human greed. There is a greed for money and there is a greed for power. But these are not the usual pitfalls that engulf the scientist. For him there is a greed that is just as ugly. It is a greed for glory, a self-centered, ruthless seeking for the credit of a great name upon Earth. It is the greed that will filch a finding from a trusting friend, that will snatch the credit from another's hand.

Ladies and gentlemen, there is only one motive that is powerful enough, not only to hold man's greed in check always and under all circumstances, but to make him really unselfish in all his dealings with his fellowmen. Ethics alone will not do it when the crucial occasion comes. The only motive that is strong enough is Christian charity, the charity that makes us love each other not only to the extent of the Golden Rule, but that we love one another as Christ has loved us--- "greater love than this no man hath, that he lay down his life for his friend." That is unselfish cooperation and it is a high ideal that is held up to us in the Bowie Medal. It makes one feel small indeed in accepting tonight's award. I thank the Committee and you, Sirs, Mr. President and Admiral Colbert.

Transactions, American Geophysical Union Volume 29, Number 3 June 1948

GRAVITY AND MAGNETIC INVESTIGATIONS IN NEW ENGLAND

George Prior Woollard

Abstract--This paper presents a history of gravity and magnetic work in the New England area; a discussion of the significance of this work and types of anomalies studied; a discussion of geologic interpretations derived from these studies in general; interpretations of regional and local anomalies in the New England area; and a discussion of the need for additional work.

Introduction

Since the Earth's gravitational field and magnetic field recognize no political boundaries, it is impossible to discuss adequately the gravity and magnetic relations in any political unit without including adjacent areas. Therefore, for the purposes of this paper all the territory east of the Hudson River, Lake Champlain Valley, and south of the St. Lawrence River out to the edge of the continental shelf will be included in this discussion of gravity and magnetic investigations in New England.

Investigations of the gravitational field and the magnetic field in this expanded New England area are limited to a fairly detailed gravity and magnetic survey of the Cortlandt Complex near Peekskill, New York; a reconnaissance gravity and magnetic survey of Cape Cod and Marthas Vineyard, Massachusetts; a regional network of gravity reconnaissance traverses over the land area; four gravity reconnaissance traverses across the continental shelf area; a single magnetic reconnaissance traverse running north-south from Concord, Massachusetts, into Quebec; a network of magnetic stations at which the principal magnetic elements have been established by the United States Coast and Geodetic Survey and the Dominion Observatory of Canada; a local detailed magnetic survey in Westchester County, New York; and local gravity and magnetic surveys in the Maritime Provinces and the province of Quebec. Since the last group have little bearing on New England proper, they will not be considered further.

The locations of the various gravity reconnaissance traverses are shown in Figure 1, and it is seen that a fair gravity network has been established over the area on a regional basis. No map is presented for the magnetic investigations since they consist primarily of magnetic declination measurements which data have little geologic value in this area without auxiliary magnetic data which are lacking. In some parts of the country it has been possible to use such observations for geologic purposes [JENNY, 1932], but in areas where the surface rocks may be characterized by marked changes in magnetic susceptibility such as in New England, it is impossible to tell whether these magnetic data represent the regional or a local anomalous magnetic field.

History of investigations

The first geophysical measurement made in New England proper of which there is a record [HOWE and KNAPP, 1938], was the determination of the magnetic declination at Round Hill, Connecticut, by the United States Coast and Geodetic Survey in 1833. No other measurements were apparently made until 1844 when determinations of magnetic declination, inclination, and horizontal intensity were made at Stamford, Connecticut, by the United States Coast and Geodetic Survey. In passing it is interesting to note the change in these magnetic values since 1844 at Stamford as shown in Table 1.

Table 1--Change in magnetic values at Stamford, Connecticut, 1844-1935

Year	Declination	Inclination	Horizontal intensity
	°	°	γ
1844	6 36 W	73 2	17,890
1935[a]	12 31 W	72 24	17,220

[a] 1935 is the last year for which there are published comparative data at this writing.

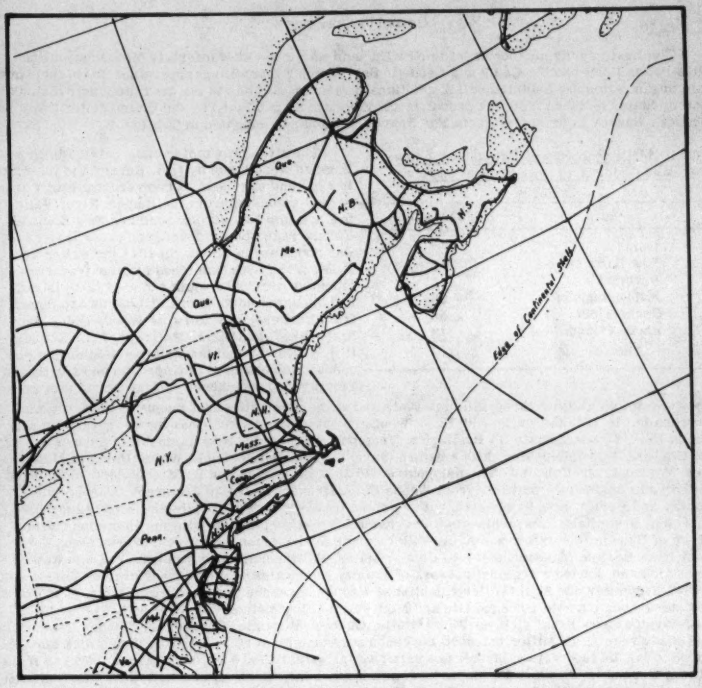


Fig. 1--Location of gravity traverses in New England and vicinity

From 1844 to the present some 470 magnetic stations have been established by the United States Coast and Geodetic Survey in New England, and their general distribution by States and time is indicated in Table 2.

Table 2--Statistics on United States Coast and Geodetic Survey magnetic stations in New England

State	No. of stations	Date of first station
Maine	135	1849
New Hampshire	56	1849
Vermont	48	1876
Massachusetts	161	1844
Connecticut	56	1833
Rhode Island	13	1844
Total	469	

Other magnetic work in New England consists primarily of observations of the vertical component of the Earth's magnetic field. In 1940 R. A. Geyer made a survey in the Highland gneiss area of Westchester County, New York. In 1942 A. P. Crary, J. L. Worzel, R. J. McCurdy, and the writer made a reconnaissance survey of Cape Cod and Marthas Vineyard, Massachusetts. In 1946 a survey of the Cortlandt Complex near Peeksill, New York, was made by the writer and Nelson Steenland; and in 1947 a reconnaissance survey was made by C. L. and R. Drake from Concord, Massachusetts, into Quebec.

No formal air-borne magnetometer surveys have been made in the area although during the War as a by-product of anti-submarine patrols by the Navy using air-borne magnetic detectors, "highs" were observed in Long Island Sound and in Cape Cod Bay.

Gravity surveys

The first gravity measurement in New England was made at Worcester, Massachusetts in 1899 by the United States Coast and Geodetic Survey using a pendulum apparatus. Since that time, this organization has established 112 additional pendulum stations in the area, and their distribution by States as taken from the pendulum-gravity data as published by the United States Coast and Geodetic Survey in Principal Facts For Gravity Stations, is indicated in Table 3.

Table 3--Distribution of United States Coast and Geodetic gravity stations in New England

State	No. of stations
Maine	3
New Hampshire	3
Vermont	1
Massachusetts	36
Connecticut	58
Rhode Island	12
Total	113

The first gravimeter observations in New England were made by J. B. Hersey and the writer in 1940 and consisted of two reconnaissance traverses extending from the Hudson River Valley to Cape Cod Bay across southern New England. The average station spacing on these traverses was about seven miles. In 1941 the writer and E. M. Woollard established similar traverses along the north and south shore of Long Island and along the north shore of Long Island Sound from Yonkers, New York, to Woods Hole, Massachusetts. In 1942 A. P. Crary, J. L. Worzel, R. J. McCurdy, and the writer established a reconnaissance survey of Cape Cod and Marthas Vineyard, Massachusetts. Stations on this survey were set up at about three-mile intervals and at the same sites that magnetic observations were made. In 1943 the writer and E. M. Woollard established a reconnaissance traverse from Woods Hole, Massachusetts to Burlington, Vermont via Nashua, New Hampshire; Auburn, Maine; and Gorham, New Hampshire, with a return traverse from Burlington to Woods Hole via Middlebury, Vermont, and Concord, New Hampshire. In 1944 the writer and E. M. Woollard established another reconnaissance traverse from Woods Hole, Massachusetts to Coaticook, Quebec via Conway and Berlin, New Hampshire, with a return traverse to Woods Hole via Derby Line, Vermont, and Greenfield, Massachusetts. That same year in cooperation with the Dominion Observatory of Canada, the writer and A. H. Miller established a reconnaissance traverse along the coast from Boston, Massachusetts to Calais, Maine. Miller continued this traverse into New Brunswick and started a regional network of gravity reconnaissance traverses over this area. In 1945 the writer and A. H. Miller established a reconnaissance traverse from Perth, New Brunswick to Quebec City via Presque Isle and Moosehead Lake, Maine, with a return traverse to Frederickton, New Brunswick via Victoriaville, Quebec; Megantic, Quebec; and Bangor, Maine. This same year A. H. Miller extended the reconnaissance network in both New Brunswick and Nova Scotia. In 1946 Nelson Steenland and the writer established a reconnaissance traverse from Ottawa, Canada to Woods Hole, Massachusetts via Cornwall, Ontario, and Bellows Falls, Vermont, and another traverse from Rutland, Vermont to Port Jervis, New Jersey via Lake Placid, Watertown, and Saratoga, New York. A detailed survey was also carried out that year over the Cortlandt Complex near Peekskill, New York by Steenland and the writer. On this survey about 200 gravity and magnetic stations were established at intervals of about one mile on a network of roads crossing the area. In 1947 C. L. and R. Drake made a regional reconnaissance survey around Lake Winapasaukee, New Hampshire, and established a reconnaissance traverse from Concord, Massachusetts to near St. Damase, Quebec via Colebrook, New Hampshire.

As far as the writer is aware there have been no other gravity or magnetic observations made in the area.

Significance of gravity and magnetic measurements

General statement

Although magnetic observations sometimes can be directly correlated with the geology of an area, it is hardly ever possible to do this with gravity observations. This difference is related primarily to the large effect of local changes in elevation compared to that due to local changes in density on gravity observations in contrast to the large effect of local changes in magnetic susceptibility on magnetic observations and the insensitivity of magnetic observations to other local factors. For example, a 16-foot change in elevation has the same gravitational effect (one mgal) as 160 feet of material with a density differential of 0.5 which is about the maximum density differential likely to be encountered. A change of one or two per cent in the magnetite content of a rock, however, will result in an appreciable change in magnetic readings. This apparent advantage of magnetic measurements is offset, however, by other factors which will be discussed later.

Reduction of data

To isolate that part of a gravity or magnetic observation that can be attributed to local geology, it is first necessary to correct or reduce the data for all other known contributing effects. Gravity observations are commonly corrected for instrumental drift, the shape of the Earth, the speed of rotation of the Earth, the elevation of the station above sea level, the mass of material beneath the surface and above sea level, and irregularities in the surface of the surrounding terrain. Magnetic observations are usually corrected for instrumental drift, for the change in the Earth's normal magnetic field with latitude and longitude, and for changes in the Earth's magnetic field during the course of a day. The residuals left after making these corrections are the anomalies, and it is these values (reflecting a combination of deep-seated, shallow, and surface geologic controls) with which the geologist must work.

Types of anomalies

Considerable confusion has been occasioned those not familiar with geophysics by the use of several types of anomalies derived from the same data. Gravity data, for example, may be reduced so as to yield Free Air anomalies, simple or complete Bouguer anomalies, Residual anomalies, and Isostatic anomalies, and the last may be computed by either of two methods based on two entirely different concepts of Isostasy. All of these have geologic significance, but the choice of anomalies depends upon the problem being investigated.

Free Air gravity anomalies--All gravity anomalies incorporate a correction for the shape of the Earth, the speed of rotation of the Earth, the elevation of the station, and instrumental drift. If no further corrections are applied, the value obtained is a Free Air anomaly. Free Air anomalies usually bear a direct relationship to the topography and are used primarily for geodetic studies and for the determination of local departures of the vertical from gravity values.

Bouguer gravity anomalies--The application of a correction for the mass of material down to sea level (the assumed surface of the spheroid used in applying the correction for the shape of the Earth) to the Free Air anomaly value yields a Bouguer anomaly. In regional studies it is customary to use a fixed density of 2.67 for the material above sea level in making this correction. In studies of local areas the actual mean density of the region down to sea level is generally used. The simple Bouguer anomaly neglects the effect of all irregularities in the surface of the adjacent terrain, and assumes a horizontal plane surface around the station at its elevation. The complete Bouguer anomaly incorporates a correction for the effect of irregularities in the surface of the surrounding terrain. This "terrain" effect seldom exceeds one mgal except in areas of pronounced topographic relief, and in New England it is doubtful whether the correction would ever exceed three mgals or average more than one mgal at a normal station site.

Since the Bouguer anomalies incorporate corrections for all the factors affecting gravity values which can be accurately evaluated, these anomalies reflect primarily the mass distribution associated with the unknown sub-surface geology, and for this reason are the ones commonly used in geologic work.

Residual gravity anomalies-- Residual anomalies are usually Bouguer anomalies which have been corrected by arbitrarily removing the bulk of the observed anomaly which is frequently referred to as the regional effect. This is done by either smoothing profiles, or by determining the mean anomaly value in an area extending about ten to 15 kms around a station and then subtracting this mean value from the Bouguer anomaly at the station. The purpose of such residual anomalies is to bring into relief small gravitational effects such as are associated with changes in surface lithology, oil structures, or ore bodies, so that they can be contoured and studied. An analogy would be isolating for study the shape of a tumor on the side of an elephant from a contour map of the elephant. The large regional anomalies, which are removed to obtain the residual anomalies, are believed to reflect primarily intracrustal changes in lithology and therefore have a definite geologic value of their own.

Isostatic gravity anomalies--Isostatic anomalies incorporate a correction for the deficiency in mass that is commonly observed in areas of high elevation. Under the Pratt theory of isostasy, which states in brief, "the mountains stand high because they are light," the correction is based on the elevation of the point of observation and applied over a crustal column extending down to 113 km below sea level. Under the Airy theory of isostasy which visualizes constant density crustal blocks floating on a denser sub-stratum with downward projecting "roots" beneath the areas of high elevation, the correction is based on the density differential of crustal and sub-crustal material and the elevation of the point of observation. This correction which is applied to the Bouguer

anomalies is much the same computed by either method. The geologic value of isostatic anomalies is that they show the degree of isostatic equilibrium in any area, and call attention to mountains formed as a result of overthrusting, horst tectonics, or deep-seated crustal displacements which do not have a "root," by exaggerating the positive anomalies associated with them. For most geologic studies, Bouguer and residual Bouguer anomalies are more satisfactory than isostatic anomalies in that they involve no corrections based on assumptions as to the intra-crustal mass distribution.

Magnetic anomalies--Magnetic anomalies are more or less standardized in that it is customary to correct the observed magnetic values for instrumental drift, the diurnal change in the Earth's magnetic field, and the normal change in the Earth's magnetic field with latitude and longitude. Residual anomalies determined as outlined under gravity anomalies are also sometimes used. The advent of the air-borne magnetometer may be expected in increase the use of residual magnetic anomalies where data are obtained at two elevations or a ground survey is made in connection with an air-borne survey. With such data the residuals would be obtained by subtracting the smoother isogam surface of the survey made at the higher elevation from that obtained at a lower flight level or a ground survey.

Geologic significance of gravity and magnetic anomalies

Both gravity and magnetic anomalies reflect horizontal changes in an equipotential field which can be related to geologic causes. In the case of gravity measurements the control is the mass distribution which reflects changes in the densities of individual rock masses, their size, and depth of burial. In the case of magnetic measurements, the magnetic field is complicated not only by variations in the magnetic susceptibility of different rock masses, their size, and depth of burial, but also by the orientation of the rock masses and their mineral particles relative to the lines of force of the Earth's magnetic field, the geometry of the rock masses, and the separation of induced north and south poles. A further complication is the frequent development and uneven distribution of paramagnetic minerals on the flanks of intrusives as a result of contact metamorphism. With so many variables and with overlapping effects from deep-seated, shallow, and surface rock masses, it is not surprising that gravity and magnetic anomalies are not always readily interpreted in terms of geology. However, as has been indicated, the use of residual anomalies frequently makes it possible to separate that part of the anomaly caused by deep-seated geologic factors from that related to near-surface and surface geology. It is also possible to determine from the width of any anomaly area a maximum depth for the disturbing factor causing it. This same anomaly, however, could be produced by an infinite number of shallower bodies having progressively wider physical dimensions and lower contrast in physical properties as the surface is approached. As a result a unique geologic solution can never be obtained from magnetic or gravity data alone. The combination of gravity and magnetic data may frequently serve to identify the type of lithology giving rise to an anomaly and thus remove one of the unknowns, but the main value of the data will always be qualitative rather than quantitative. Gravity and magnetic surveys, therefore, are most useful as reconnaissance methods in that they define areas in which it might be profitable to do more geologic work, carry out seismic work, or drill, but it is frequently not until the completion of a drilling program that the geology reflected by the gravity or magnetic anomalies is known.

Results of gravity and magnetic investigations in New England

Gravity surveys

All of the gravity observations made by the United States Coast and Geodetic Survey, 113 stations, were reduced so as to yield Free Air, complete Bouguer and isostatic anomalies based on the Pratt theory of isostasy. The balance of the observations, except for the traverses across the continental shelf and one traverse through central New Hampshire which have not been computed as yet, were reduced to yield simple Bouguer anomalies. LONGWELL [1943] has published maps contoured on the basis of the Free Air, Bouguer, and Isostatic anomalies for southern New England, and a preliminary Bouguer iso-anomaly map of northern New England has been published [WOOLLARD, 1944]. The results of the gravity surveys in the Maritime Provinces have also been reported [MILLER, 1946, and WOOLLARD, 1945]. There are no published reports covering gravity investigations in New England since 1944. The Bouguer iso-anomaly map shown in Figure 2, however, does include the results of all investigations in the area through 1946. An examination of this map shows that the anomalies contour in a systematic manner, and that although there is an obvious need for additional data in certain areas, particularly Maine (see Fig. 3), the major regional features are fairly well delineated. The magnitude of the regional anomalies is seen to vary from -70 mgals to over +40 mgals.

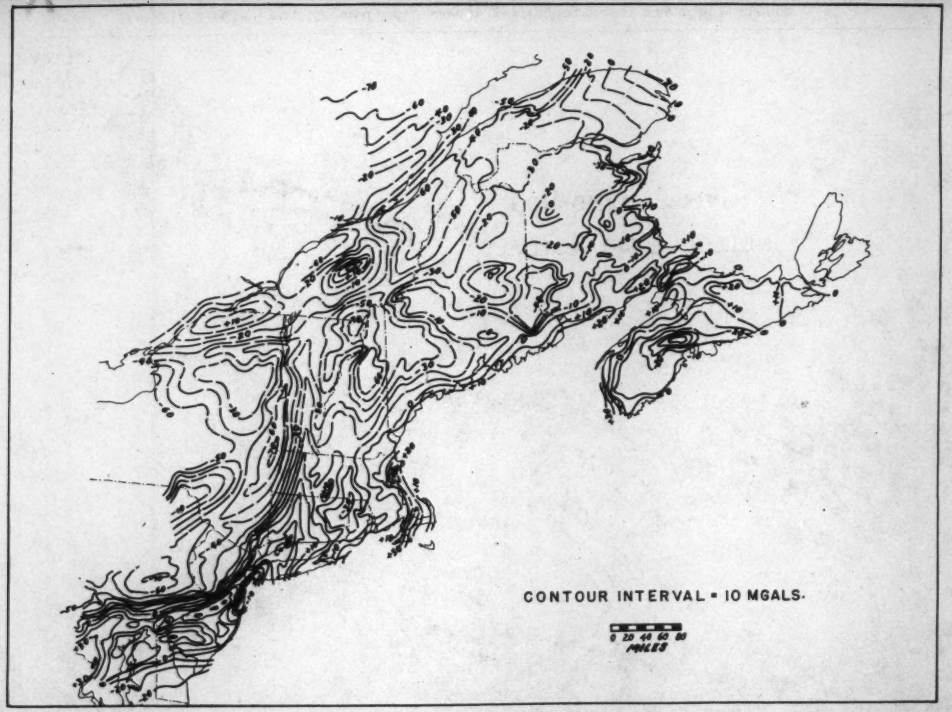


Fig. 2--Bouguer iso-anomaly gravity map of New England and vicinity

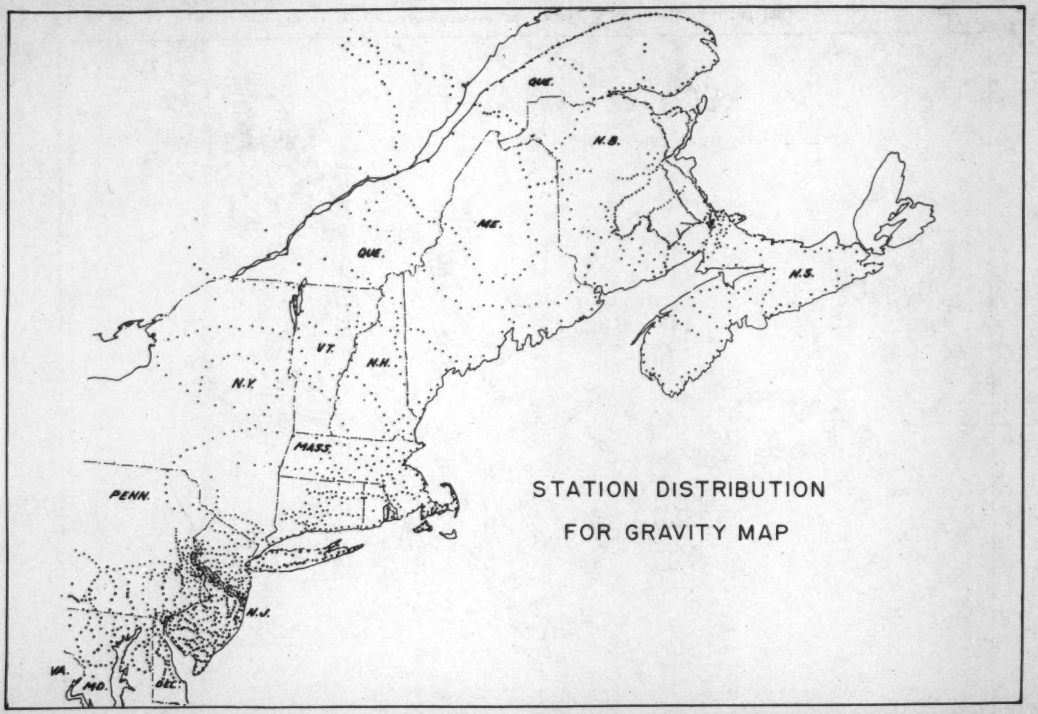


Fig. 3--Gravity-station distribution used in constructing gravity map of New England

If the generalized gravity map of Figure 4 is examined in connection with the geologic map of the region, the following relations are found: (1) Most of the anomaly "structures" parallel the strike of surface-geologic structure. (2) The White Mountain area of New Hampshire is characterized by marked negative anomalies. (3) The Green Mountain area of Vermont is underlain by a gravity "high." (4) The Adirondack area of New York is underlain by a gravity "high." (5) Marked negative anomalies are associated with the Paleozoic granites of New Brunswick and Nova Scotia. (6) The granite area near the international boundary to the west of Colebrook, New Hampshire, is characterized by marked negative anomalies. (7) Positive anomalies are found in the

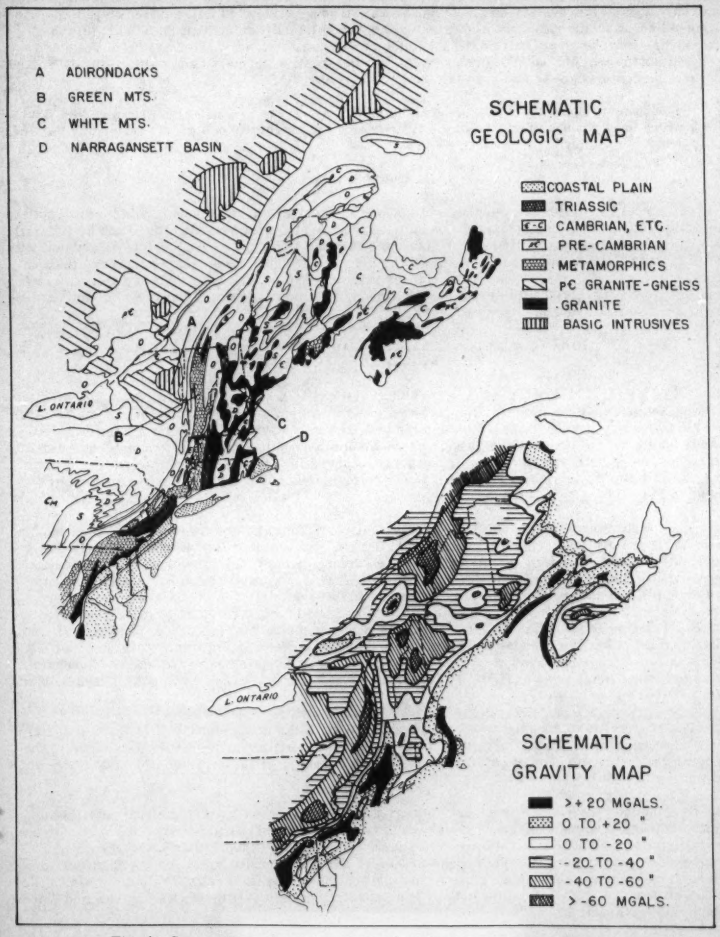


Fig. 4--Comparison of gravity map and geologic map of New England

areas of pre-Cambrian rocks in New Brunswick. (8) The asbestos deposits of Quebec occur at the center of a marked positive anomaly area.

Many of the large regional anomalies, however, do not appear to be related to the surface geology in any way, and the following is a list of the more prominent of these: (1) The positive anomaly area running along the Maine Coast and embracing the Bay of Fundy area; (2) the marked positive anomaly belt running from Cape Ann across Cape Cod and Marthas Vineyard in Massachusetts; (3) the marked positive anomaly area occurring to the west of the Connecticut Triassic Basin and extending southward beneath the Coastal Plain of New Jersey; (4) the marked negative anomaly area at the western end of Long Island extending southward into New Jersey; (5) the pronounced negative anomaly area centering on the Rhode Island-Connecticut State line; (6) the marked negative-anomaly belt on the east side of the Hudson River-Lake Champlain Valley extending southward into eastern Pennsylvania; (7) the positive anomaly area north of the Adirondack Mountains centering near Malone, New York.

In addition to these there are several other anomaly areas in Quebec, Maine, and New Brunswick which have not been included since their extent and magnitude are poorly defined by the available data.

Magnetic surveys

As far as the writer has been able to ascertain, there are no published reports on magnetic investigations in New England and the results of the few magnetic surveys with which he is familiar can be summed up as follows: (1) There are isolated sharp magnetic "highs" associated with local gravity "highs" on Cape Cod. (2) Strong magnetic "highs" occur on the southern flank of the Cortlandt Complex. (3) There are marked magnetic "highs" in the Highland gneiss area of eastern New York. (4) There appears to be a magnetic counterpart of the gravity "highs" crossing Cape Cod Bay and Long Island Sound.

Geologic interpretation of gravity and magnetic surveys in New England

LONGWELL [1943], in his study of gravity relations in southern New England, found that he could establish very little correlation between either the known geologic structure of the area or the surface-rock density distribution and the gravity data reduced so as to yield Free Air, Bouguer, and Isostatic anomalies. He concluded that the anomalies for the most part appeared to reflect intra-basement changes in lithology if not actual changes in the thickness of the granitic crust similar to those postulated by GLENNIE [1932] to explain some of the large gravity anomalies found in India.

L. L. Nettleton, in an unpublished communication to Longwell and the writer, pointed out that if residual gravity anomalies had been used in the study of southern New England, a much better correlation could have been established with the surface geology. He also prepared a residual iso-anomaly map of the area. From this map (see Fig. 5), which Nettleton has kindly permitted me to use in this paper, the following relations are observed: (1) The schist and gneiss area extending northward from Manhattan Island, New York, is characterized by positive anomalies. (2) The Triassic Basin areas in Connecticut are negative anomaly areas except locally over the diabase sills which are positive anomaly areas. (3) The eastern half of the Newark Triassic Basin in New Jersey is a negative anomaly area. (4) The gabbro intrusive in eastern Connecticut is a positive anomaly area. (5) The Naraganset Basin of carboniferous sediments in Rhode Island is a positive anomaly area.

The above results correlate well with the densities of the rocks in each of the areas, and although no quantitative studies have been made using these data as far as the writer is aware, the general qualitative agreement obtained is sufficient to demonstrate the value of the use of residual anomalies in New England.

One anomaly area which is brought into greater relief by the use of residual anomalies and which shows no obvious geologic correlation, is the positive anomaly area between Worcester and Springfield, Massachusetts. This area is mapped as being pre-Cambrian sedimentary schists, but from the gravity data it would appear that there are high-density basic rocks either near or at the surface in the region. Another anomaly area brought out by the residual values for which there is no obvious geologic correlation is the "low" paralleling the coast between Plymouth and Weymouth, Massachusetts.

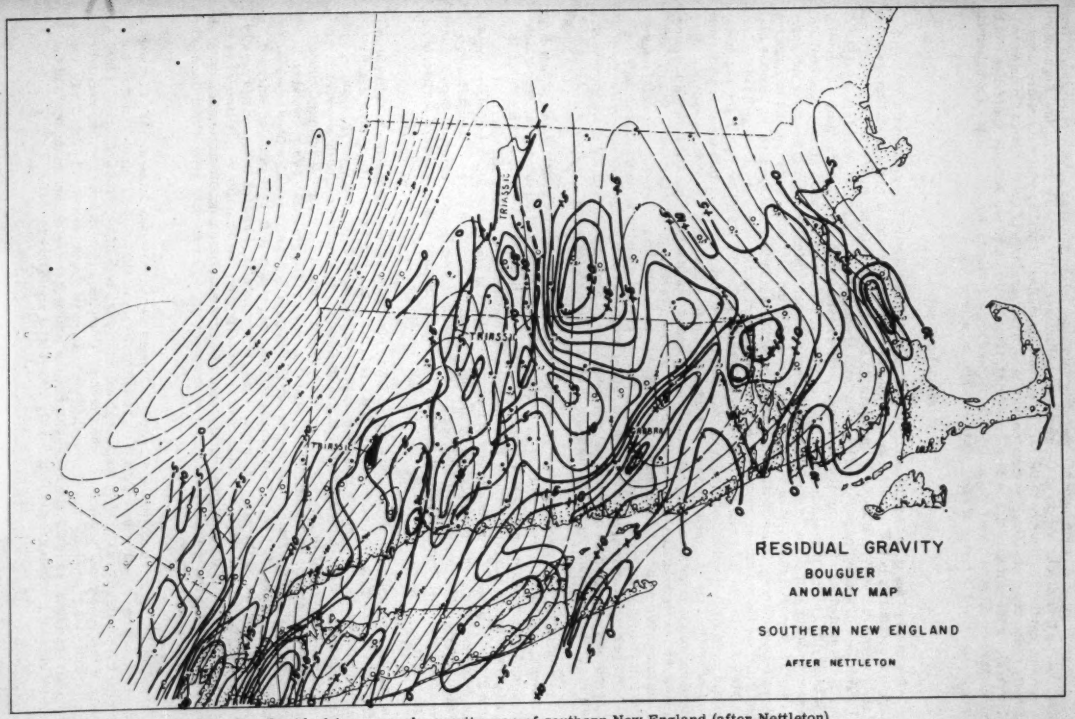


Fig. 5-- Residual iso-anomaly gravity map of southern New England (after Nettleton)

As residual anomalies have not been determined as yet for the area outside of southern New England, further discussion as to the geologic significance of the gravity data in New England will have to be confined primarily to the large regional anomalies. Locally, where there are large density contrasts such as are associated with the norite intrusives of the Cortlandt Complex in New York or the salt deposits in New Brunswick, Canada, the observed Bouguer anomalies can be correlated directly with surface or near-surface geologic features, but many of the anomalies can only be explained in terms of deep-seated crustal structure.

The regional anomalies

The marked negative anomaly belt running up the Hudson River-Lake Champlain Valley is part of a continuous belt of negative anomalies extending from Alabama to the St. Lawrence River Valley where it either terminates or merges with cross-cutting structural trends (see Figs. 2 and 4). This belt of anomalies parallels the structural trend of the Appalachian Mountain system and is associated with the zone of overthrusts on the eastern side of these mountains. A parallel belt of positive anomalies which appears to originate in the Green Mountain area of New England is seen to occur just to the east of the negative anomaly belt. Similar pairs of negative and positive gravity anomaly belts have been observed in connection with other major mountain ranges and with island arcs. Geologically the negative anomaly belt is believed to mark the position of the "root" of the mountains postulated by Airy which tectonically may have developed from: (1) Down-buckling of the crust as postulated by VENING MEINESZ [1940] to explain the negative gravity anomaly belts associated with island arcs; (2) low angle faulting within the crust with subsequent vertical displacement because of over- and under-thrusting of the sheared ends; or (3) thickening of the crust as a result of accumulating sediments in a geosyncline. It is not the purpose of this paper to discuss the relative merits of these various hypotheses, and it is sufficient to indicate that the anomaly in question is believed to be related to an increase in crustal thickness rather than a change in intra-crustal lithology. The belt of positive anomalies paralleling the belt of negative anomalies is believed to reflect a thinning of the crust and the proximity of higher-density basic rocks beneath what was originally an arched section of the crust formed at the time of the postulated crustal thickening in the negative anomaly area.

In support of this hypothesis, it is found that the axis of the positive anomaly belt in New England and New Jersey coincides with the probable position of the axis of the structural arch which tilted the Triassic sediments in New Jersey to the west and those in Connecticut to the east. It is also observed as indicated earlier that the Green Mountain anticline lies on the axis of this same gravity "high." This occurrence of a gravity "high" in connection with a mountain range where the anomaly cannot be explained by the densities of the rocks forming the mountains indicates that these mountains have no "root" and are not isostatically compensated. Such a mountain presumably resulted from overthrusting or else is related to some primary upward displacement of the crust.

The gravity minimum associated with the White Mountains of New Hampshire is believed to reflect a true "root" beneath these mountains. It is also observed that large regional negative gravity anomalies occur over the granite outcrops to the west of Colebrook, New Hampshire, in eastern Maine and western New Brunswick, and in Nova Scotia. Since most of these areas are of relatively low elevation, an isostatic correction would not materially alter the anomaly values, and it would appear that the anomalies are related directly to the granites. In a personal communication, D. C. Skeels has advised the writer that similar relations have also been observed over granites in Finland. There it was found necessary to postulate that the granites extended to a depth of ten kms on the basis of the observed gravity anomalies and the difference in density between the granites and the surrounding rocks. As no figures are available at this time as to the density of the rocks in the areas under consideration, it has not been possible to compute the probable depth to which the granites extend. However, there is every reason to believe that the depths will be great.

The "high" associated with the Adirondack Mountains and that associated with the Cortlandt Complex, a norite intrusive near Peekskill, New York, characterized by a high of 30 mgals, but covering too small an area to have much regional effect, can both be explained in terms of the density of the basic rocks present. On the Cortlandt Complex the mean density of the norite intrusive is about 3.2 whereas the surrounding gneisses have a mean density of about 2.67. There are no data available as to the actual densities in the Adirondack region, but on the basis of the lithology present a somewhat smaller density differential would be expected.

Other regional-anomaly "structures" such as the "high" crossing Cape Cod and the "low" centering on the Connecticut-Rhode Island State line, are probably related to intra-basement changes in lithology, the "highs" representing high-density basic rocks, and the "lows," granitic rocks with densities slightly below that of the bulk of the rocks in the region.

Magnetic anomalies

Not much can be said about the geologic significance of the magnetic anomalies in New England since the data are so few. The occurrence of local magnetic "highs" on Cape Cod which correlate with gravity "highs" would suggest the presence of a rock similar to gabbro immediately below the coastal-plain sediments in the areas of the anomalies.

The magnetic survey of the Cortlandt Complex in New York showed no well defined correlation between the magnetic data and the lithology or the gravity data. A belt of marked positive magnetic anomalies was found to be present along the south side of the intrusive, but it could not be correlated with any of the available geologic data. Away from the norite massif a very strong magnetic high was found in the Fordham gneiss which appeared to be related to a large pegmatite dike.

The magnetic survey by R. A. Geyer in Westchester County, New York, showed the presence of several large magnetic anomalies in this area, and petrographic studies indicated that these were probably related to the amphibolites in the area.

The indications of magnetic "highs" in Long Island Sound and Cape Cod Bay, in the same general areas where there are gravity "highs", would indicate that the basic rocks, postulated on the basis of the gravity data alone, are probably gabbroic in character.

Future investigations

There is a definite need for additional gravity and magnetic work in New England as well as supplementary geologic and seismic studies. The existing gravity reconnaissance network needs to be extended as as to develop at least a 40-mile grid pattern over the entire area. Magnetically, the area is essentially unmapped, and in view of the geologic complexity of the region and probable rapid changes in the magnetic susceptibility of the rocks, an air-borne magnetic reconnaissance survey or ground survey on which stations are set at one to two-mile intervals is needed.

From the results of complete regional gravity and magnetic reconnaissance surveys, it should be possible to obtain a better understanding of the regional geology of the area and to delineate areas in which it would be desirable to carry out detailed geologic and geophysical measurements.

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HORIZONTAL EARTH MOVEMENT, VICINITY OF SAN FRANCISCO, CALIFORNIA

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Abstract--Earth movements in California caused by seismic activity in the Earth's crust have been measured by precise surveys at different intervals of time since the 1906 earthquake. Surveys made in 1947 give positive evidence of a slow continuous movement of the area west of the San Andreas Fault, relative to the area east of the Fault. The outer coastal area is moving northwestward at an annual rate of about five cm per year and has a total displacement of three meters since 1880, the date of the first precise surveys.

Additional surveys are in progress at the present time for the purpose of determining the extent of the area in which this movement is occurring as well as the magnitude of the movement.

For many years the United States Coast and Geodetic Survey has conducted a program for the study of earth movement in California in connection with earthquake investigations. Triangulation and traverse have served as a basis for the studies of horizontal movement. Because of the limitation of funds and urgent requests for surveys in other areas, it has not always been possible to accomplish the work which seemed most desirable for such studies. However, there have been opportunities in recent years to re-survey critical areas at the time additional control was being established.

In 1947 the Survey was asked to cooperate in establishing an urban network of triangulation in the bay region near San Francisco. Several cities in that area cooperated in making precise surveys of triangulation and traverse. Since the project was to be connected to the federal network, it was considered advisable to re-observe the basic control along the coast. The primary stations, originally observed in 1880-1885, had been re-observed in 1906 and 1922 [BOWIE, 1928] for the purpose of re-establishing the positions which were known to have been displaced at the time of the 1906 earthquake.

When the 1947 observations were compared with the earlier observations at the old stations, discrepancies were noted which were larger than could be considered accidental errors. Comparison with the data from the 1880-1885, 1906, and 1922 surveys showed changes that, in many instances, were progressive. Whenever the directions of lines crossing the San Andreas Fault were compared, the changes were systematic and the magnitudes of the differences were closely proportional to time. This preliminary investigation suggested a different type of analysis from that generally used when studies of earth movement have been made.

The well-established method of determining the change of position of the points in the scheme was used first. The data for the four surveys were adjusted in a scheme that was considered identical for each set. In each case the line Mocho-Mt. Diablo (see Fig. 1) was considered as unchanged or fixed in position. It was necessary to make this assumption since some of the surveys have not extended further into the interior. However, since these points are about 35 miles east of the Fault such an assumption is reasonable and could not have any serious effects in determining relative movement.

Figure 1 shows the results obtained from these four adjustments. The displacements determined from the adjustments are shown as vectors. The stations on the southwest side of the fault-line show continuous movement in a direction that is generally parallel to the Fault. The shifts of the points on the northeast side of the Fault are of about the order of magnitude that could be expected from accidental errors.

The suggestion of continuous movement of the area to the southwest of the Fault was first advanced by the late H. F. REID [1933]. Other seismologists, notably Perry Byerly and John P. Buwalda, have encouraged the re-observation of the triangulation so that the magnitude of this movement could be determined. The method of determining movement by changes in positions is not always satisfactory. When the scheme is large, the accumulated errors of the triangulation

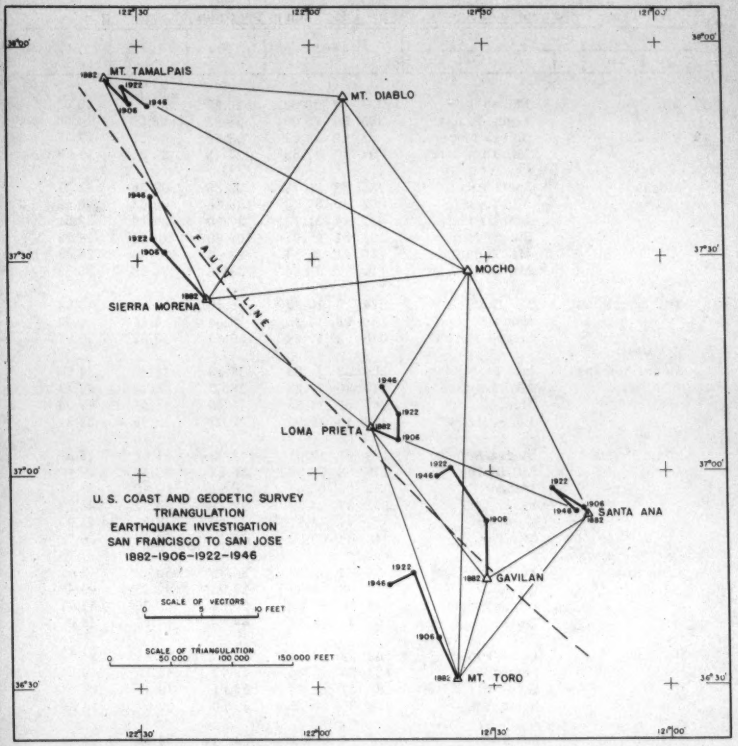

Fig. 1--Results obtained from four triangulation adjustments showing displacements as vectors

net can indicate changes that are not real, and the actual position error at any station can be in excess of any change caused by earth movement.

Because of this limitation of the method of change of position, a differential method was used in which the relative movement was determined from the differences of azimuth of the lines of the net. The strength of figure is a very important factor in position determination but does not affect the azimuth. The accuracy of the directions and the number of lines through which the azimuths must be computed are the limiting features of this method.

The azimuths of the various lines of this scheme as computed for the four surveys are listed in Table 1. The changes in azimuths for these lines are listed in Table 2 with the data for the 1880-1885 survey being used as the reference. The azimuths of the lines parallel to the Fault do not show any systematic or progressive changes. However, the lines crossing the Fault do show such changes.

These changes in azimuth may be transformed into relative horizontal movement by assuming that the motion is in a direction parallel to the Fault and by giving proper consideration to the length of the line for which the differences of azimuths are being tested. The results of this study are listed in Table 3. The lines which were parallel to the fault could not be used, but all other

Table 1--Azimuths of lines in Figure 1 for each of the times of observation

Line		1882	1906	1922	1947
From	To	° ′ ″	″	″	″
Mt. Diablo	Mocho	324 44 30.62	30.62	30.62	30.62
	Loma Prieta	355 50 25.00	23.23	23.09	24.08
	Sierra Morena	33 44 58.33	63.79	65.27	67.32
	Mt. Tamalpias	94 40 27.59	25.48	26.91	25.53
Mocho	Santa Ana	335 38 00.78	02.36	02.36	01.21
	Mt. Toro	2 36 37.18	38.18	39.63	40.92
	Loma Prieta	32 14 31.19	27.60	29.10	32.51
	Sierra Morena	83 51 05.01	09.60	10.82	14.25
	Mt. Tamalpias	118 41 25.54	24.98	25.59	25.45
	Mt. Diablo	114 57 38.88	38.88	38.88	38.88
Mt. Tamalpias	Mt. Diablo	274 15 18.25	16.16	17.58	16.22
	Mocho	298 03 14.38	13.84	14.44	14.32
	Sierra Morena	335 52 47.84	50.33	50.89	50.91
Sierra Morena	Mt. Tamalpias	156 03 21.68	24.13	24.69	24.69
	Mt. Diablo	213 30 31.23	36.67	38.14	40.19
	Mocho	263 32 37.83	42.40	43.61	47.04
	Loma Prieta	308 44 19.95	20.65	18.96	21.21
Loma Prieta	Sierra Morena	129 01 12.01	12.75	11.06	13.31
	Mt. Diablo	175 52 58.37	56.62	56.47	57.46
	Mocho	212 03 62.48	58.91	60.40	63.81
	Santa Ana	292 37 24.52	24.11	25.63	28.29
	Gavilan	323 44 43.87	41.29	42.81	44.90
	Mt. Toro	342 04 03.99	06.13	07.09	08.72
Santa Ana	Mt. Toro	38 44 32.53	36.30	38.49	43.05
	Gavilan	57 08 29.99	38.92	43.65	49.46
	Loma Prieta	112 59 27.98	27.54	29.06	31.74
	Mocho	155 49 42.62	44.18	44.18	43.05
Mt. Toro	Loma Prieta	162 12 29.89	32.00	32.94	34.57
	Mocho	182 34 40.74	41.73	43.15	44.44
	Gavilan	197 21 19.86	22.01	20.89	22.82
	Santa Ana	218 31 02.73	06.50	08.67	13.21
Gavilan	Mt. Toro	17 24 31.39	33.54	32.43	34.36
	Loma Prieta	143 56 23.96	21.35	22.86	24.95
	Santa Ana	236 58 10.40	19.33	24.05	29.84

lines are shown. A comparison of the values in Table 3 with the lines in Figure 1 shows that when two points are on the same side of the Fault the shifts are not progressive or systematic, but that for the five lines crossing the Fault at a good angle, the shifts are systematic and remarkably consistent. The data for these five lines are re-listed in Table 4, showing the mean displacement for the various time intervals and the average annual rate needed to produce such shifts.

The results of these studies show that, for a strip about 40 miles in width and 100 miles in length, there is positive evidence of movement of the outer area at a rate approximately five cm per year. The question of the extent of the area to which this movement is confined is of primary importance. The re-survey of 1947 did not furnish sufficient data to define the northern or southern limits, nor does the survey extend far enough west of the Fault.

At the present time a triangulation party of the Survey is completing a re-survey of the network shown in Figure 2. There are a few supplemental points to be included in the area north of San Francisco which are not shown on the sketch. When the data for this season's work are received, a similar analysis will be made so that further information will be available concerning the extent and magnitude of the movement.

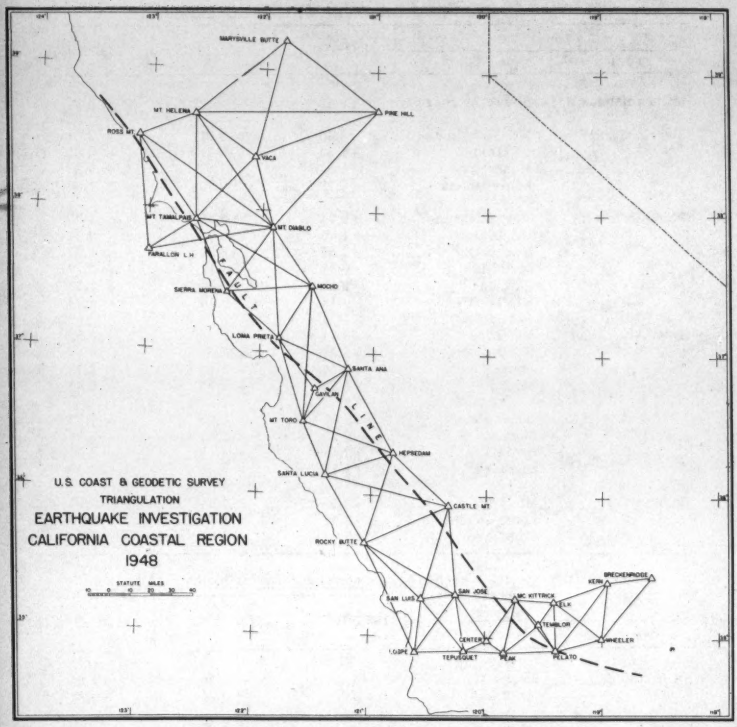

Fig. 2--Triangulation network being re-surveyed

Table 2--Differences of azimuths (from Table 1)

Line		1882-1906	1882-1922	1882-1947
From	To			
		"	"	"
Mt. Diablo	Mocho	0.00	0.00	0.00
	Loma Prieta	-1.77	-1.91	-0.92
	Sierra Morena	+5.46	+6.94	+8.99
	Mt. Tamalpias	-2.11	-0.68	-2.06
Mocho	Santa Ana	+1.58	+1.58	+0.43
	Mt. Toro	+1.00	+2.45	+3.74
	Loma Prieta	-3.59	-2.09	+1.32
	Sierra Morena	+4.59	+5.81	+9.24
	Mt. Tamalpias	-0.56	+0.05	-0.09
	Mt. Diablo	0.00	0.00	0.00
Mt. Tamalpias	Mt. Diablo	-2.09	-0.67	-2.03
	Mocho	-0.54	+0.06	-0.06

Table 2--Differences of azimuths (from Table 1) Concluded

Line		1882-1906	1882-1922	1882-1947
From	To			
		"	"	"
Mt. Tamalpias	Sierra Morena	+2.49	+ 3.05	+ 3.07
Sierra Morena	Mt. Tamalpias	+2.45	+3.01	+ 3.01
	Mt. Diablo	+5.44	+6.91	+ 8.96
	Mocho	+4.57	+5.78	+ 9.21
	Loma Prieta	+0.70	-0.99	+ 1.26
Loma Prieta	Sierra Morena	+0.74	-0.95	+ 1.30
	Mt. Diablo	-1.75	-1.90	- 0.91
	Mocho	-3.57	-2.08	+ 1.33
	Santa Ana	-0.41	+1.11	+ 3.77
	Gavilan	-2.58	-1.06	+ 1.03
	Mt. Toro	+2.14	+3.10	+ 4.73
Santa Ana	Mt. Toro	+3.77	+ 5.96	+10.52
	Gavilan	+8.93	+13.66	+19.47
	Loma Prieta	-0.44	+ 1.08	+ 3.76
	Mocho	+1.56	+ 1.56	+ 0.43
Mt. Toro	Loma Prieta	+2.11	+ 3.05	+ 4.68
	Mocho	+0.99	+ 2.41	+ 3.70
	Gavilan	+2.15	+ 1.03	+ 2.96
	Santa Ana	+3.77	+ 5.94	+10.48
Gavilan	Mt. Toro	+2.15	+ 1.04	+ 2.97
	Loma Prieta	-2.61	- 1.10	+ 0.99
	Santa Ana	+8.93	+13.65	+19.44

Table 3--Displacements needed to produce changes of azimuths in Table 2

Line		1882-1906	1882-1922	1882-1947
From	To			
		m	m	m
Mt. Diablo	Sierra Morena	+1.73	+2.20	+2.86
	Mt. Tamalpias	-0.86	-0.28	-0.84
Mocho	Mt. Toro	+0.76	+1.85	+2.83
	Loma Prieta	-0.88	-0.51	+0.32
	Sierra Morena	+1.79	+2.26	+3.60
Mt. Tamalpias	Mt. Diablo	-0.85	-0.27	-0.83
Sierra Morena	Mt. Diablo	+1.73	+2.19	+2.85
	Mocho	+1.78	+2.25	+3.58
Loma Prieta	Mocho	-0.88	-0.51	+0.33
Santa Ana	Mt. Toro	+1.00	+1.59	+2.81
	Gavilan	+1.33	+2.04	+2.90
Mt. Toro	Mocho	+0.75	+1.82	+2.80
	Gavilan	+0.33	+0.16	+0.46
	Santa Ana	+1.00	+1.58	+2.80
Gavilan	Mt. Toro	+0.33	+0.16	+0.46
	Santa Ana	+1.33	+2.04	+2.90

Table 4--Relative displacements for five lines crossing the Fault

Line	1882-1906	1882-1922	1882-1947
	m	m	m
Mt. Diablo-Sierra Morena	+1.73	+2.20	+2.86
Mocho-Sierra Morena	+1.78	+2.26	+3.59
Mocho-Mt. Toro	+0.76	+1.84	+2.82
Santa Ana-Mt. Toro	+1.00	+1.58	+2.80
Santa Ana-Gavilan	+1.33	+2.04	+2.90
Mean	+1.32	+1.98	+2.99
Annual rate	+0.055	+0.050	+0.046

A unique feature of the year's program includes the re-observation of astronomical azimuths at Mt. Toro which were observed in 1885, 1906, and 1923. Preliminary results from the 1948 astronomical observations verify the movement shown by the triangulation. The method of using astronomical azimuths is independent of the triangulation and offers an excellent check on the data obtained by triangulation. It also merits further use because of the lower cost as compared with that of triangulation.

By the use of horizontal control surveys, geodesists have the opportunity of aiding seismologists and geologists in determining not only the actual movement but also the magnitude of the stresses that are being built up in the Earth's crust. For three generations, engineers of the Survey have continued a program of precise measurements which form the basis of our present studies. It is our responsibility in this generation to perpetuate the program that has been in progress, and to initiate new procedures and methods which will permit greater use of existing data, not only by geodesists but also by scientists engaged in other brancnes of geophysics.

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EMPIRICAL CORRECTIONS TO CONSTANT ABSOLUTE VORTICITY TRAJECTORIES

Ralph S. Bortman

Abstract--This paper describes a method for determining empirical corrections to constant absolute vorticity trajectories by computing the distance between the observed and prognosticated ridge or trough line at a given latitude. This method is applied to trajectories computed on five-day mean charts over the Northern Hemisphere between zero and 180° W. The area studied is subdivided into 11 parts wherein each subdivision is associated with some specific orographic feature or distinguishing thermal structure. Results indicate that corrections to trajectory forecasts over the mountainous areas of western North America are westward, while corrections over central and eastern portions are eastward. Corrections over the oceans are generally small.

One of the major problems of both short- and long-range forecasting is the understanding of the mechanisms which cause changes in the various flow patterns aloft. An important contribution of the solution of this problem was made by ROSSBY [1940], who developed a method for forecasting the path of an individual air parcel by assuming constant absolute vorticity. (Such constant absolute vorticity paths will hereafter be referred to as CAV trajectories.) However, it has become clear that in order to utilize these CAV trajectories to best advantage in practical forecasting work they must be modified. Attempts in this direction were made by BRIER and DORSEY [1944] and later by FULTZ [1945], all of whom carried out their studies on daily charts. In their earlier work, Brier and Dorsey correlated the observed wind direction with the direction given by the vorticity method at successive time intervals along the vorticity path. In the latter study, Fultz compared the CAV trajectory with an approximation to the true particle trajectory. Both projects showed that vorticity paths could be put to good use but were subject to serious deviations from observed paths.

It was felt that CAV trajectories could be computed on five-day mean charts. These mean charts are characterized by a relatively steady state of flow which brings out the broad features of the flow pattern. These characteristics are in good agreement with Rossby's major simplifying assumptions, namely, (1) steady state (no local change in circulation); (2) no change in velocity along the path of the air parcel; (3) broad currents with no shear; (4) absence of solenoidal fields; (5) absence of convergence or divergence; and (6) absence of friction.

On each mean chart it is possible to select several points which appear to obey the assumptions made by Rossby, and which thus have promise of reliable prognostic value. However, even after these points have been selected, there are still other factors that are likely to enter into the picture, including convergence and divergence and the presence of solenoidal fields. These phenomena to some extent can be associated with orographic features, warm and cold water currents, and other permanent climatic factors. In view of this, it should be possible to determine a set of empirical corrections that would be applicable in their respective areas of the world.

The first step was to compute corrections which compensate for the effects of these influences. The easiest objective method was to note, after a given time interval, the distance between the observed ridge or trough line (defined as a line connecting points of maximum or minimum latitudes of the contours) and the vorticity ridge or trough line (first characteristic point for CAV trajectories originating at inflection points). The time interval was the time necessary for the air particle to reach its first characteristic point. Figure 1 illustrates the procedure followed.

Lines H_1, H_2, and H_3 represent the contours of the mean chart on which the vorticity path, defined by points T_0, T_1, T_2, and T_3 is constructed. Line A is the position of the ridge line on this chart, and line B is the observed position of the ridge on the next five-day mean chart one-half week later. Since the time between charts is not the same as the time it takes the particle, following a constant absolute vorticity path, to reach its first characteristic point, it is necessary to find by interpolation the ridge position, say at C, after the time interval T_1. This is done by assuming that the speed of motion of the system from position A to position B is constant, so that after the time interval T_1, the system moves from A to C. The correction is then measured from point T_1 to point C in degrees of latitude. (All measurements are made at the maximum or

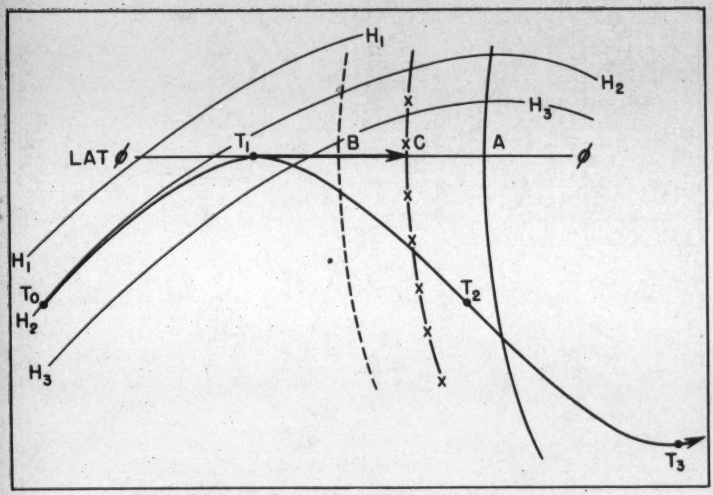

Fig. 1--Schematic flow pattern showing computation procedure

minimum latitude indicated by the CAV trajectory.) When the observed position falls to the east of the vorticity position the correction is considered positive; in the opposite case, negative.

In order to insure that the same trough or ridge is being studied from map to map some simple rules of continuity were established: Firstly, that no new trough or ridge forms between the inflection point and the trough or ridge line; and secondly, that the trough or ridge line extends on the succeeding chart to the latitude indicated by the first characteristic point.

The data for the project consisted of all the mean 700 mb and 10,000-foot charts from December 1943 to February 1946. These charts were obtained from the files of the Extended Forecast Section of the United States Weather Bureau. Approximately 1500 vorticity paths were constructed. One half of the Northern Hemisphere, roughly from zero to 180° W, was studied and divided into 11 areas (see Fig. 2). These areas were arrived at by drawing natural climatological and topographic boundary lines. Then another dividing line was drawn roughly along the 45° N latitude circle. These areas were further modified for specific features and to fit the general homogeneous groupings of corrections for one winter season. The data for the other two of the three winters studied fell into much the same general groupings, so no further modification of the areas was made.

A rapid glance at these areas shows that areas I, V, and VIII are dominated by mountain ranges; areas II and IX are comparatively flat land mass areas; areas IV and VII are predominantly ocean areas; and areas VI and X are also ocean areas but have the added features of a land mass to their west and the warm gulf stream flowing through them. Areas III and XI are areas influenced by the European continental land mass.

All the cases studied were grouped according to the area in which their first characteristic point was found. Those falling on boundary lines were placed in the area to the north or in the area toward which the correction arrow pointed if they fell on the longitudinal dividing line.

The resulting corrections were averaged separately for troughs and ridges and for each area for each of the four seasons (where winter was taken as the months December, January, and February). In those areas where there were 20 or more cases the standard deviation was computed. On another chart each case was plotted, showing the initial wind direction and speed and the direction of the correction. This produced a strikingly uniform picture in some of the areas, particularly in areas V and II (see Fig. 3).

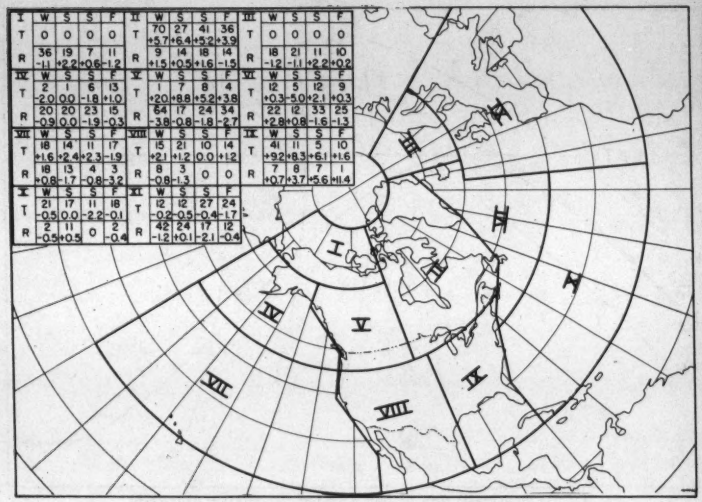

Fig. 2--Chart showing areas used for studying constant vorticity path; the tables contain the empirical corrections obtained for the various areas

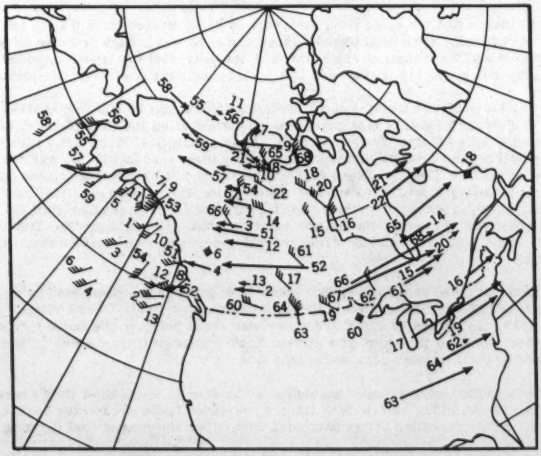

Fig. 3--Direction and magnitude of corrections, Areas II and V; data included are for December 1943 and 1944; initial wind direction and speed (in Beaufort) are indicated by barbed arrows; direction and magnitude of corrections are indicated by heavy arrows; numbers on winds and corrections identify individual cases

The data can best be evaluated by going over the results for all the areas for the winter season. Wherever possible it will be worthwhile examining these corrections for specific areas to see if any conclusions about the physical basis for the empirical corrections can be drawn.

In the upper left corner of Figure 2 there is a table giving the results for each area for each season. The upper number in each box is the number of cases; the lower number is the average correction taken with regard to sign. Standard deviations are not given in the table but will be discussed below. The upper sets of figures apply to troughs and the lower to ridges. The results for spring, summer, and fall are based on two years of data and the results for winter on three years of data.

In discussing these results, the underlying factor to be kept in mind is that when there is no wind shear across the current convergence causes a particle to increase its cyclonic curvature or decrease its anticyclonic curvature; divergence has the opposite effect. Hence a ridge line will form farther to the west under divergence than if under convergence or no influence at all. In Figure 1 the particle that started from T_0 apparently experienced convergence because the observed ridge line is not at point T_1 but at C, meaning that the actual path was less anticyclonic. This approach can be generalized by the simple rules: (1) A positive correction (system observed to the east of the trajectory's first characteristic point) associated with a northerly flow indicates divergence; with a southerly flow, convergence. (2) A negative correction implies that the northerly flow is undergoing convergence and the southerly flow divergence.

The fact that the particle deviates from the vortical path does not mean that the deviation is entirely attributable to convergence or divergence. The use of the words convergence and divergence in connection with these corrections denotes the type of modification that occurred but does not necessarily mean that the departures might not be caused by some other influence. However, it will be pointed out later that consideration of the possible physical factors responsible for the corrections make it seem plausible that in some cases divergence is the important one.

Starting with areas V and VIII in winter, it can be seen that, on the whole, the corrections for troughs are positive and for ridges negative. This indicates a divergence-type influence operating on both northerly and southerly flows. In this case it is fairly easy to arrive at a physical explanation. The column of air approaching and passing over the mountains undergoes compression and lateral stretching, causing divergence to operate. Consistency in results is shown by the standard deviation of 3.4 degrees of latitude computed for the 64 winter cases of ridges in area V. This standard deviation is of smaller magnitude than the average correction for this area.

Areas II and IX show large positive corrections for troughs and small positive corrections for ridges. These indicate a large divergence-type correction associated with northerly flow and a small convergence type with southerly flow. It is quite safe to assume that a good part of the trough correction can be attributed to divergence accompanying the marked subsidence found in the fresh polar air that would be associated with northerly flow. FULTZ [1945] found similar corrections in the same area and attributed them to the same cause. The standard deviation for the 70 cases of troughs in area II was 7.1 and in area IX, for 41 cases, it was 7.4. These are large deviations and indicate perhaps the important effect of individual synoptic situations in determining the corrections.

In areas IV, VII, VI, and X the average corrections are small. The general conclusion might be that these ocean areas exert very little climatic influences and that the individual corrections are related to the particular synoptic conditions that prevailed. A consideration of the large divergence-type corrections observed in areas II and IX, however, which disappear when particles move into areas VI and X, indicates that in these later areas there is a strong counterbalancing force in operation. This force may be the result of cold polar air moving out over warm water. This warm water creates a strong solenoidal field and also by warming the air from below introduces convergence. The standard deviations for the ridge cases in area IV and VI are 4.0 and 4.9, respectively.

Area I is rather interesting because of the complete absence of troughs during the entire period of study. The ridge corrections are of a weak divergence type in winter and fall and convergence type in spring and summer. The standard deviation for winter is 2.8, which is comparatively small.

The two remaining areas, III and XI, show convergence-type corrections with troughs and divergence type with ridges. This is more or less a reversal of the general trend.

The results for the rest of the seasons tend to show the same characteristics in lesser degree. In Area IX note the decrease of the divergence-type correction during the warmer season. The seasonal changes in area I have already been discussed. Areas V and VIII show little change throughout the year, indicating, as pointed out earlier, that the correction is primarily caused by the effect of the mountains.

One of the first conclusions to be drawn from this part of the study is that the corrections are definitely a function of the synoptic situations as well as of climatological features. This is evident from the large standard deviations that were obtained in several areas. On the other hand, in certain areas, such as V, VIII, II, and IX, the corrections applied as constant factors are definitely of practical forecasting value.

In general, there was good agreement between the corrections and the studies at New York University which implied that in the eastern part of the United States northerly flow is associated with sinking motion and therefore divergence, and southerly flow is associated with upward motion [MILLER, 1946]. There is also good agreement between these results and those of NAMIAS and CLAPP [1944] which showed, as should be expected from the empirical corrections computed in the present study, that observed wave speeds exceed those indicated by the wave formula in the eastern part of the United States. These findings of Namias and Clapp, applicable to the eastern parts of the United States, are not necessarily applicable elsewhere. In view of this, one should be cautious in applying the general rules in other regions since the climatological picture changes considerably.

The empirical corrections shown in Figure 2 can be used to good advantage. But in using them one should be familiar with the variability of the particular correction and, as a further caution, should be sure that the vorticity path under consideration has its beginning in a suitable air current.

The next phase of the study was an attempt to improve the prognostic value of CAV trajectories beyond the indiscriminate use of a constant empirical correction in all situations. The first step was to determine the extent to which CAV trajectories could be used to obtain the motion of troughs and ridges on five-day mean charts. This was done by correlating the prognostic displacement of a trough or ridge as indicated by CAV trajectories with the observed displacement of the trough or ridge in the number of hours necessary for the particle to reach its first characteristic point. The interpolation procedure to determine the observed position has been described elsewhere in this report. In Figure 1 the distance AT_1 is the prognostic displacement and the distance AC the observed displacement. Eastward motion of the observed system is considered positive and westward motion negative. The correlation was done separately for troughs and ridges and seasons in all those areas having 20 or more cases. The results are listed in Tables 1 and 2.

Table 1--Correlation between prognostic and observed displacement for troughs

Area	Winter	Spring	Summer	Fall
II	0.43	0.30	0.21	0.58
VIII	...	0.15	...	...
IX	0.35	...	...	...
X	0.52	...	...	...
XI	...	0.41	...	-0.03

Table 2--Correlation between prognostic and observed displacement for ridges

Area	Winter	Spring	Summer	Fall
I	0.50	...	...	...
III	...	0.38	...	...
IV	0.47	0.16	0.19	...
V	0.35	...	-0.05	0.29
VI	0.59	...	0.42	0.20
XI	0.52	0.52	...	...

They show that in all but two of the areas checked the correlations are positive. The majority of the areas lacked sufficient data to compute correlation coefficients, indicating that the study would have to be extended to include many more years to yield comprehensive results all year round for all 11 areas.

In general, the correlations show a decrease in the reliability of CAV trajectories during spring and summer and a maximum in winter. This is consistent with the reliability of most forecasting techniques and reflects poorer definition of flow patterns in the warm seasons.

In winter the correlations range between 0.35 and 0.59. These values are not remarkably high, but should be of some forecast value, especially since CAV trajectories are independent of a large number of the common methods used in forecasting. The inadequacy of observations over the ocean causes some unreliability in the data and thereby tends to lower the correlation coefficients in those areas.

The correlations were sufficiently high to warrant the computation of regression equations to express the observed displacement (see AC in Fig. 1) as a function of the prognostic displacement (see AT_1 in Fig. 1). Some of the regression lines for winter are shown in Figure 4. With the exception of area IX they show similar slopes and vary for the most part in the X- and Y-intercepts. The X-intercepts are comparable, though with the opposite sign, to the average corrections discussed earlier in this report but are by no means equal to them.

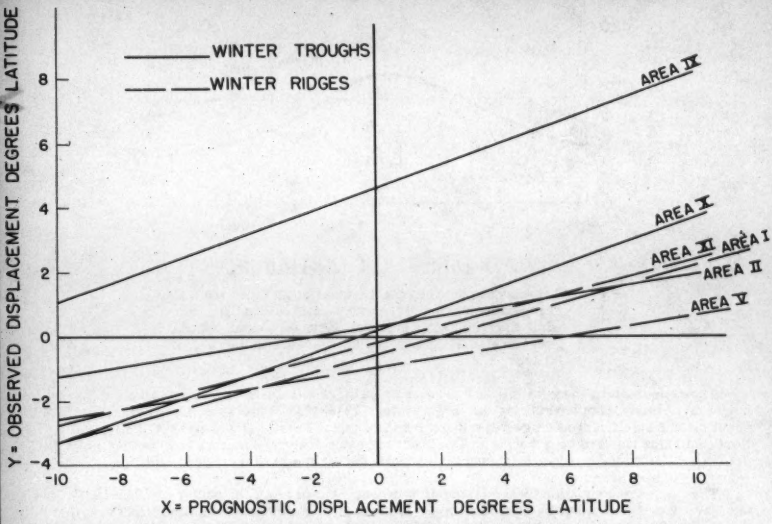

Fig. 4--Regression lines for the winter season showing observed displacement (Y) as a function of prognostic displacement (X); the prognostic displacement is obtained from the first characteristic point of the constant vorticity trajectory; solid lines refer to trough computations and broken lines to ridge computations

The regression method gives a better estimate of the displacement than does the use of an average correction, since it is determined by a method of "best fit." The average correction can be shown by statistical considerations to be inferior to the regression method. These regressions give forecast displacements for a time interval which is approximately the average of the quarter periods of each of the individual vorticity trajectories. Since systems on mean charts move slowly, no large discrepancy is likely to occur if we use this average time interval for all cases. The procedure in using these regression equations consists of multiplying the displacement obtained by the regression equation by a factor which extrapolates this value out to the desired time period. In the Extended Forecast Section of the United States Weather Bureau, the time period generally used is 96 hours.

A further step to improve the forecasts consisted of a study of the residuals obtained by subtracting the regression forecasts from the observed displacements. These residuals were graphically correlated with the parameters latitude and longitude of the initial point of the trajectory and with the wind speed and direction at that point. The wind-speed parameter gave the most interesting results (see Fig. 5 for example). Practically all the graphs indicate that where the initial wind speed is low the regression forecast gives a position too far to the west. Conversely, where the speed is high positions are forecast too far to the east. In general, as shown in Figure 5, the wind speed which separates positive and negative residuals is approximately the average wind speed for the cases used in the particular area in question.

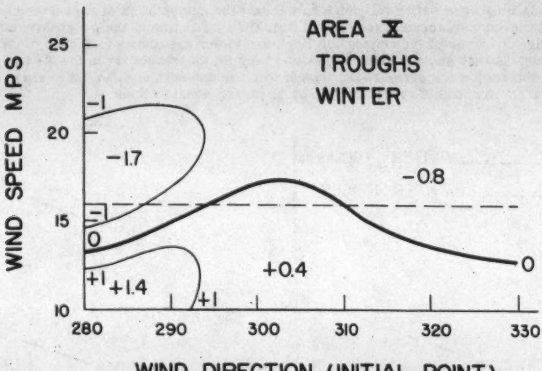

Fig. 5--Relationship between the residual departures from the regression curve and the two variables wind speed and wind direction; troughs, Area X, winter; numbers on graph are smoothed values of residuals in degrees of latitude

The representativeness of the data used in the project was checked by averaging the 700 mb height departures from normal for the three winters 1943-1944, 1944-1945, and 1945-1946. The results show significant average departures for the central Pacific and eastern Atlantic, while North America appears near normal. The chart indicates that the Aleutian Low and the ridge in the eastern Atlantic were more intense than normal during the period considered.

The regression equations were tested on independent data from the winter of 1946-1947. The test gave poor results, but by no means negative ones. It must be borne in mind, however, that this particular winter, as pointed out by NAMIAS [1947], was one of the most unusual in meteorological history.

In evaluating the results of this study, it must be remembered that it is of an empirical nature and for that reason the greatest success will be attained in average situations. In addition, the regressions were computed in only one-fourth of the possible trough-ridge-area-season combinations. Until more data become available it will be necessary to apply the average corrections to CAV trajectories in those areas for which no regression equations were computed.

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AN "ELECTRICAL MEMORY" FOR STEPPING RECORDERS

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Abstract--Methods of storing impulses applied to a stepping type recorder during the recording and homing cycle, and of transferring the stored record to the main record after homing is completed, are here outlined.

Introduction

Meteorological and other recorders, such as wind-speed maximeters [see "References" at end of paper, IVES, 1946a], which employ a stepping switch, or group of them, in conjunction with an indicator, chart recorder, or printer, must either incorporate quick-return mechanisms in the stepping devices, or lose a part of the record during the indicating (or recording) and homing (resetting to zero) cycle.

Quick-return arrangements, when applied to stepping mechanisms having a large number of contacts, usually require a great deal of maintenance, are quite noisy, and have short operating periods between major overhauls. For a large number of required contacts, most of the need for special quick-return stepping switches can be met by cascading or decading standard ten-point spring-return stepping switches, such as the "Minor" switch, made by the Automatic Electric Company. Cascaded switches are required at the rate of one for each ten contacts; decaded switches are required at the rate of one for each power of ten, or residual fraction thereof, in the required contact number.

In many instances, loss of a finite small part of the record, of known duration, is either statistically correctable, or is unimportant. When this is true, use of standard equipment, with statistical correction where needed, is the preferred recording method.

Duplex operation

Where a "100 per cent" record is necessary, two recorders, controlled by a suitable switching mechanism, can be used alternately, one recorder being "in circuit" at any given time; the other either going through the recording and homing cycle, or resting. Both can be arranged to operate the same indicating or printing instrument, so that a continuous record on a single chart is obtained. This procedure is analogous to duplex telegraphy or Class B amplification. This procedure, while entirely workable, is somewhat involved, and may require a relatively enormous amount of equipment.

Electrical impuse storage

To reduce the complexity of the recorder, while still maintaining the "100 per cent" record, experiments were conducted with an "electrical memory," so designed that impulses received during the recording and homing cycle were stored by a small subsidiary recorder, and added to the main record after homing was completed.

Preliminary experiments consisted of tests in which a condenser was charged by impulses received during the homing cycle of the main recorder, and later discharged intermittently by an oscillator or interrupter, so that the number of impulses produced by the discharge was equal to the number of charge increments (impulses) received.

Two promising "electrical memory" devices resulted from these experiments. One consisted of a gas-discharge triode, with the charged condenser connected in the grid-cathode circuit to operate as a neon oscillator, and a plate relay to operate the main stepping switch. The other consisted of a relay oscillator [IVES, 1946b], powered by the charged condenser, and operating the stepping switch of the main recorder by means of subsidiary contacts.

Both recorders could be adjusted to reproduce a given small number of evenly-spaced impulses accurately after any time lapse desired, up to about 15 minutes, but any great variation in the number or spacing of the incoming impulses, or the time lapse, resulted in an electrical "lapse of memory."

Electro-mechanical impulse storage

Introduction--Because a standard ratchet-type stepping switch does not slip back once it is set to a given position, it is incapable of "forgetting." Experiments with electrical memories incorporating this type of impulse storage resulted in the development of several very successful devices, one of which will be outlined here. Numerous alternative devices, embodying the same, or similar, principles, are possible.

Primary controls--For wind recorders, primary controls consist of an anemometer and a clock. The function recorded will be the number of Nths of a mile of wind in M minutes, N being the number of anemometer contacts per mile of wind movement, and M the clock contacting interval. Both constants can be varied within wide limits preferably by proper choice or adjustment of the instruments or by use of submultipliers; the latter method should be avoided when possible.

The anemometer, usually distant from the recording instruments, is connected in a local circuit consisting of battery A and relay 1 as shown in Figure 1. Any reasonable number of other devices can be operated by this same anemometer by use of additional contacts on relay 1.

The anemometer contact closures, which are of unequal spacing and duration, produce like closures of the contacts of relay 1. In the limiter circuit, consisting of battery B, relay 2, and condenser C_1, these are converted to closures of the contacts A' which have the same spacing as those of the anemometer, but of uniform short duration, such as 0.1 sec, determined by the circuit constants.

The clock, which drives a cam-operated switch, controls another limiter circuit consisting of battery C, relay 4, and condenser C_2, so that the closure of the contact of relay 4 is of constant short duration, such as 0.15 sec, determined by circuit constants, even though closure of the cam switch is several seconds in each cycle.

Closure of the contacts of relay 4 causes relay 3 to pull in, which starts the recorder reset cycle, and controls the "memory" element. When relay 3 is in up position (upper contacts A''-E'' closed; contacts X'' and W'' open), the memory element is out of circuit, and each closure of the anemometer contacts advances the continuous rotation stepping switch one contact clockwise. Control circuit is from the positive side of battery B, through lower A' contacts of relay 2, through upper A'' contacts of relay 3, through stepping switch coil, and to the negative side of battery B.

Indicating or recording functions are controlled by bank 3 of this stepping switch, here shown as a single element, although it may be a cascaded or decaded combination, functioning as a single unit.

Reset--When the contact of relay 4 closes in response to a closure of the clock switch lower contact, relay 3 is momentarily energized from battery C, and the main armature pulls down and latches into position. Lower contacts A''-E'' of relay 3 close when the armature pulls down; contacts W'' and X'' close a small fraction of a second later, when the latch moves into holding position.

The main stepping switch is now connected as a self-stepper, the circuit being from the positive side of battery B, through contacts B'' of relay 3 to the arm of bank 2 of the stepping switch; thence through the main contacts to the off-normal contacts, which act as an interrupter, and finally to the negative side of battery B. With this connection, the switch will step clockwise continually until the self-stepping circuit is broken, a procedure normally taking place when the arms reach zero contact (home position), where the release coil of relay 3 is energized, and the system is reset for recording.

The release coil of relay 3 is wired in a self-disconnecting circuit, through contacts C'' which are controlled by the main armature, so that when the armature is released (latch pulled back) and rises, the contacts open, and the release coil (relay 3) is deenergized.

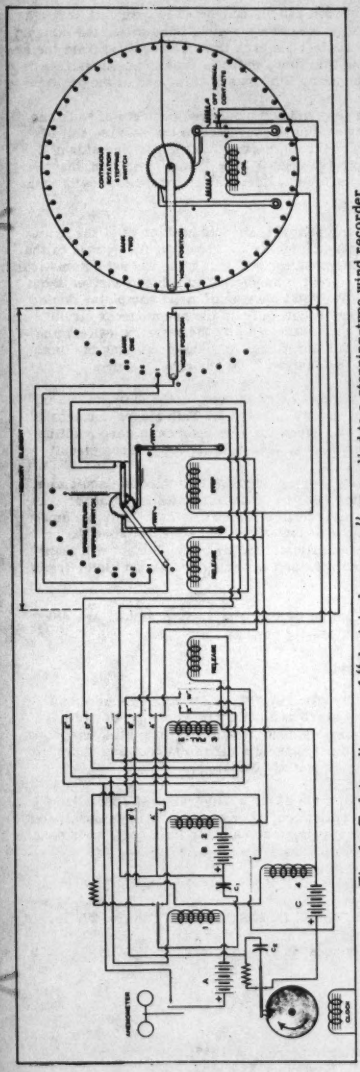

Fig. 1--Skeleton diagram of "electrical memory" as applied to a stepping-type wind recorder

Alternative reset--In place of a ring-connected contact bank on the stepping switch, and a set of off-normal contacts, a relay oscillator or similar interrupter can be used in a rather obvious circuit, to return the stepping switch arms to zero, or any other desired position.

Interlocks--To prevent conflict of functions, resulting in a missed or duplicated count, when the anemometer and clock circuits close approximately in unison, a relatively complicated interlock system is necessary. To reduce these conflicts to a statistically negligible value, a relatively simple interlock system, requiring no additional items of equipment, is shown in Figure 1.

Minimization of temporal overlaps is accomplished by use of the limiters already described. By reducing the duration of the controlling impulses, the probability of overlap is greatly reduced.

To prevent resetting while an anemometer impulse is coming in, the reset circuit is disabled for the duration of the incoming impulse by opening of the contacts B′ of relay 2.

So that an anemometer impulse will not be recorded twice, once on the main recorder and once on the "memory" recorder (to be described later), the anemometer circuit is opened during the time that relay 3 is changing position. Contacts E″ open the anemometer circuit when the armature starts to pull down, and the circuit remains open until the latch moves to "holding" position and closes contacts X″. As the duration of the anemometer contact closure is far greater than that of the switchover interval, no incoming signal is lost by this momentary opening of the circuit.

Opening of the anemometer circuit, however, releases the armature of relay 1, so that, unless preventive measures are taken, the limiter condenser C_1 is discharged, and reclosure of the circuit would result in a second impulse being sent into the stepping circuit by the limiter. To eliminate this spurious signal, the discharge circuit of C_1 is opened at the beginning of the switchover interval by the opening of contacts E″ of relay 3, and reclosed at the end of this same short interval by the closure of contacts W″.

With these interlocks, conflicts of functions are made extremely infrequent, but are not entirely eliminated. More complex interlocks, embodying anticipatory and time-delay devices, may eliminate all conflicts, but in so doing, will so greatly increase the number of components subject to failure that their utility is questionable.

Memory--To "remember" the number of impulses received from the anemometer circuit during the reset cycle, a subsidiary stepping switch, shown in Figure 1 as a spring-return

stepping switch, although it may be a cascaded or decaded unit, is connected into circuit, through lower contacts A'' of relay 3. During the time that this subsidiary switch, here called the memory switch, is in circuit, the arm is stepped upward one contact for each impulse received from the anemometer circuit. If N impulses are received during this time, which is exactly coextensive with the reset cycle of the main stepping switch, the arm is on the Nth contact at the end of the period.

Contacts of the memory switch are wired to correspondingly numbered contacts of bank one of the main stepping switch. The arm of the memory switch is connected to the release coil of relay 3 through its contacts C'', the arm of bank one of the main switch to the positive side of battery C. When both switches are at the Nth contact, and relay 3 is in "down" position, the release coil of relay 3 is energized, and the system switches automatically from reset (with memory) to record.

With this arrangement, if resetting starts from any position, such as contact 23 of the main switch, and five impulses are received and "remembered" during the reset cycle, the arm of the main stepping switch will proceed clockwise past home position, and will come to rest automatically at the fifth contact beyond it. Further progress will equal the number of impulses received from the anemometer circuit before the next reset cycle. The total number of steps completed during a time cycle, therefore, will be the sum of the impulses received from the anemometer circuit and recorded by the main stepping switch, and those "remembered" by the memory switch, and later transferred, by advance of zero position, to the main switch. This number, being the total number of anemometer contact closures, constitutes the desired "100 per cent" record.

Resetting of the memory switch to zero occurs automatically as soon as the main switch is placed in recording position by release of the main armature of relay 3. This closes contacts D'' (of relay 3), energizing the memory switch release coil. When the arm returns to zero position by spring action, the tail contacts of the memory switch open, deenergizing the release circuit.

Correction for recorder delay--When the printing, chart-recording, or indicating equipment controlled by the third bank of the main stepping switch requires a definite time interval for completion of the record, the stepping circuit only of the main switch can be opened by suitable auxiliary controls for the necessary time, and closed either at the end of that time, or when the required recording process is completed, regardless of duration. The memory element will then record all incoming impulses received during the recording and resetting cycles, and later transfer the stored record to the main record.

Connections of these recorder controls, which must be kept as simple as possible, are determined by the type of recording device used, and are usually obvious.

Conclusions

The "electrical memory" here outlined is representative of a large family of recorder adjuncts filling special, rather than general, needs in research and industrial control. Use of a "memory" in place of quick-return devices permits employment of standard, long-life, telephone equipment, instead of special switching mechanisms usually having a high first cost and short operating life, with a resultant lowering of costs and maintenance demands.

Extension of recorder systems embodying "memory" to cover a wide range of specialized needs is theoretically possible. Advisability of such application, after possibility is demonstrated, must be determined for each individual case, major governing factors being first cost, maintenance cost, and ratio of operating time to down time.

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THE ABSORPTION FACTOR IN COUNTING ALPHA RAYS FROM THICK MINERAL SOURCES

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Abstract--The total measured alpha emission from a thick layer of powdered sample of each of a number of minerals and rocks of known uranium and thorium content agreed well with the emission predicted for the samples on the basis of a source absorption proportional to the square root of the atomic weight of the elements comprising the source. Thus, the measurement of combined uranium and thorium in most minerals and rocks may be made by the simple count of alpha rays above a thick layer of the sample, and the application of the appropriate absorption factor. Counting equipment particularly suitable for the range of activity of common rocks is described which will count all of the alphas emitted above the plane of the source having a residual range greater than a specified amount, thus requiring no calibration.

Introduction--The use of uranium and thorium as trace elements in geological processes, and in the measurement of geologic time by the helium method, commonly requires the measurement of these elements down to amounts as low as 10^{-7} g of uranium or thorium per g of sample.

Measurements in this range are too low for beta- or gamma-ray counting, but may be made by separate radon and thoron determinations as described in references listed by EVANS and GOODMAN [1944]. These determinations, especially the thoron, are tedious and consume the sample. Thin-source total alpha counting as described by the above authors provides a measurement of the total alpha activity from the combined U and Th series, and when used in combination with a radon measurement eliminates the lengthy thoron analysis.

In this research the objective was to extend the method of total alpha-ray counting to the practical use of thick sources, by accurately evaluating the absorption of alpha rays by the source. This required experimental testing of the present theory of alpha-ray ranges in solids.

The thin sources used by Evans and Goodman were not permitted to exceed 15 microns, so that all the alpha rays occurring in the source were able to leave with enough residual velocity to be detectable. Finely powdered samples were deposited on an alumimum disc as suspensions in alcohol, and thickness determined by weighing. The advantage was that the absorption correction was only of second order importance. The disadvantages of the method were the time required to prepare the source for measurement, inaccuracy resulting from the uneveness of its deposition, and the fact that less than one-half the count per unit area is obtained than possible from a thick source.

By thick source is meant any thickness exceeding the range of the most energetic alpha ray. For massive material this would be normally any thickness over about 50 microns, but for powdered material a millimeter or more is generally used to eliminate the possibility of intergranular openings through the source at any point. It is assumed that a level-surface powdered source is equivalent to a hypothetical plane-surface solid source, since the error caused by scattering toward the interface of grazing rays is negligible. An actual plane-surface solid source prepared by polishing is not used for fear of radon loss in the heating of the surface skin during polishing.

There is a need in geology for a simple method to measure the total alpha activity of minerals and rocks, which requires a minimum of interpretation and time per measurement. Also, it is desirable to have a method that is absolute, and does not require the use of standards for calibration. It was believed that a thick-source alpha counter would best fulfill these needs, once a simple and accurate set of rules had been evolved for the determination of the absorption factor. Particularly it was desired that the Bragg-Kleeman absorption rule, to be outlined below, be tested for accuracy and used if possible.

Thin-source alpha counting is probably still the most suitable method for measuring the total alpha activity of acid igneous rocks. In this case the activity is high enough to be easily measurable by this technique, but what is more important, the activity is frequently to a large but unknown

extent in certain accessory minerals of higher density than the average. This means that the absorption factor for a thick source of this heterogeneous material could not be determined. Thus, the reduction to a minimum of the thickness of the source is necessary for accurate work. Thick-source counting on these materials may require subsidiary measurements to estimate the distribution of the activity among the minerals of the aggregate.

If the material to be measured consists of a single mineral type, or an aggregate of minerals in which the activity is fairly uniformly distributed, or an aggregate in which the activity is not uniformly distributed but in which the different minerals have nearly the same absorption, then the use of a thick source is generally both more accurate and more convenient. Basic and ultrabasic rocks, many metamorphic rocks and sediments, and most of the finer-grained flows of all types, fit into these categories.

Emission of alpha rays from a thick source--The alpha-ray emission from a homogeneous thick source caused by UI alone is as follows: If R_{UI} equals range of UI alpha rays in air in cms, μ equals ratio of range in mineral to range in air, and r equals minimum residual air range necessary for detection, then the maximum depth in the source from which rays can be counted is $\mu(R_{UI} - r)$.

The emission per second into the half-space above the source surface from a volume dy.dA at depth y within the source

$$e = (N/2)\,(1 - \cos\theta)\,dy \cdot dA$$

where N is the number of UI atoms disintegrating per sec per cm^3, and $\cos\theta = y/\mu(R_{UI} - r)$.

Total emission due to UI per cm^2 of surface

$$e_{UI} = (N/2)\int_0^{\mu(R_{UI} - r)} (1 - \cos\theta)dy = N\mu(R_{UI} - r)/4$$

If $\lambda_{UI} = 4.83 \times 10^{-18}$ = fraction of UI transformed per second; UI equals the amount of UI in mineral in gm/gm; W_{UI} equals the atomic weight of UI; and d equals the density of mineral, gm/cm^3, then

$$N = 6.06 \times 10^{23}\,UI \cdot d \cdot \lambda_{UI}/W_{UI}$$

and emission per second per cm^2

$$e_{UI} = \mu d \times 10^3[3.08\ UI\,(R_{UI} - r)]$$

For the UI series in equilibrium, the emission

$$E_{UI} = \mu d \times 10^3[3.08\ UI\,\Sigma_{UI}(R - r)]$$

where $\Sigma_{UI}(R - r)$ is the summation for all values of R in the series. Similarly, for the thorium series in equilibrium, the emission

$$E_{Th} = \mu d \times 10^3[1.03\ Th\,\Sigma_{Th}(R - r)]$$

Using the value 0.046 as the ratio of activity of the AcU series to that of the UI series as given by NIER [1939], the emission caused by the AcU series in equilibrium

$$E_{AcU} = \mu d \times 10^3[0.14\ UI\,\Sigma_{AcU}(R - r)]$$

The minimum detectable residual range r, of an alpha ray in air, was found by EVANS and GOODMAN [1944, p. 219] to be 0.5 cm for their counter. This has been found to be about the right value for counters using electrometer tube and balanced bridge circuit, with galvanometer and photographic recording. Amplifying circuits with higher noise or thresholds should be tested experimentally for this value. This can be done most easily by calibrating the counter with known sources.

Using r = 0.5 cm, and summing the ranges of the various alpha rays according to values given by HOLLOWAY and LIVINGSTON [1938] and HENDERSON and LAWRENCE [1937], as listed in Table 1, the total emission from all significant alpha emitters

$$E = \mu d(10^3)[89.41\ UI + 26.60Th]\ alphas/sec/cm^2$$

Commonly, the activity is expressed in terms of the equilibrium R_a content in gm/gm and Th content in gm/gm, and emission/cm^2/hour. In this case a convenient form is

$$E = 915\ \mu d[(Ra \times 10^{12}) + (0.105Th \times 10^6)]$$

Table 1--Summation of detectable ranges of alpha rays from UI, AcU, and Th series

UI series	Range in air R	AcU series	Range in air R	Th series	Range in air R
	cm		cm		cm
UI	2.68	AcU	2.90	Th	2.60
UII	3.21	Pa	3.57	Rdth (Av)	4.00
Io	3.09	RdAc (Av)	4.60	Thx	4.32
Ra	3.26	AcX (Av)	4.29	Tn	5.00
Rn	4.05	An (Av)	5.67	ThA	5.64
RaA	4.66	AcA	6.46	ThC (Av)	4.73[a]
RaC	6.91	AcC	5.36	ThC'	8.57[a]
RaF	3.84				
$\Sigma_{UI}R$ =	31.67	$\Sigma_{AcU}R$ =	32.85	$\Sigma_{Th}R$ =	34.86
$\Sigma_{UI}(R - r)$ =	27.67	$\Sigma_{AcU}(R - r)$ =	29.35	$\Sigma_{Th}(R - r)$ =	25.83

[a]ThC and ThC' weighted according to branching ratio of 0.34 ThC to 0.66 ThC'.
Note: RaC, AcC' and Ac omitted due to negligible branching ratios.

Evaluation of absorption factor--An approximate evaluation of μd, the absorption factor for any source material, may be made according to the empirical rule stated by BRAGG and KLEEMAN [1905], in which the stopping power of a medium consisting of a single element is proportional to the square root of the atomic weight of that element, or

$$\mu d_e = d_a\sqrt{W_e}/\Sigma f\sqrt{W_a}$$

where $d_a = 0.001226$ gm/cm^3 = density of dry air at 15° C, and 760 mm Hg, d_e = density of the element, and $\Sigma f\sqrt{W_a} = 3.84$ = sum of atomic fraction times the square root of the atomic weights of the chemical constituents of dry air. When applied to minerals or rocks

$$\mu d_m = (d_a/\Sigma f\sqrt{W_a})(f_1\sqrt{W_1} + f_2\sqrt{W_2} + \ldots)$$

where d_m = density of mineral or rock, $f_1, f_2, \ldots$ = weight per cent of first element, second element, ... in mineral or rock; $W_1, W_2, \ldots$ = atomic weight of first element, second element, ..., in mineral or rock.

GLASSON [1922] found that the stopping power of an element is proportional to its atomic number raised to the two-thirds power within the limits of small velocity variations. The Bragg-Kleeman rule and the Glasson rule both lead to similar results for many elements.

The experimental test of the Bragg-Kleeman rule for minerals and mineral aggregates was the principal purpose of this work. Direct determination of alpha-ray ranges in some minerals has been possible by measurement of pleochroic haloes. HENDERSON and TURNBULL [1934] found that the ranges in biotite agree well with the theoretical value based on the chemical analysis of the mineral.

Alpha-ray counter--The ionization chamber used in this work was constructed as part of a laboratory for helium age measurement under a grant by the Geological Society of America to one of the authors (Hurley). A sketched section is shown in Figure 1.

The chamber has a steel wall 10 cms high cut from 10 1/2 inch tubing. Base and cap plates of sheet brass have circular openings to permit the source plate and collecting electrode to enter at the bottom and top. An electrometer tube (G. E., FP-54) is housed in a vacuum-tight chamber of Shelby tubing, with a bakelite cap at the top through which the leads enter. Thé bottom of the tubing is tapered inside to fit a brass ring which has been soldered into a brass plate. The inside of the brass ring is again tapered slighly to fit a polystyrene plug which acts as an insulator for the collecting electrode. All joints are sealed with wax.

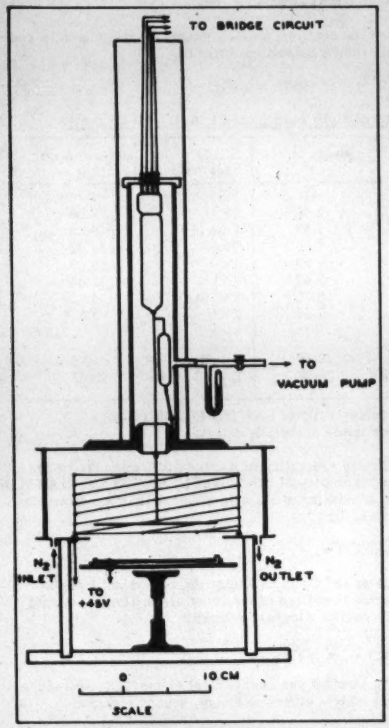

Fig. 1--Ionization chamner used for measuring radioactivity of rocks

The collecting electrode is a horizontal copper wire grid, represented by a single line in the sketch. A copper wire cage encloses the collection volume. This cage and the copper source plate are maintained at +45 volts with respect to the collecting electrode and chamber, which are at ground potential. Ions formed by alpha rays from the walls of the chamber outside of the cage are repelled, so that the background count is low considering the size of source used. The source plate is a copper disc, 14.3 cms in diameter, or with an area of 160 cm^2, and is insulated from the base plate by a bakelite disc one-half cm thick, recessed to a depth of two mm to serve both as a holder for the source disc and as a retaining wall for the sample.

The pulse from the electrometer tube is recorded photographically from a Leeds-Northrup Type R galvanometer in a balanced bridge circuit. Recording equipment and circuit are covered by the references listed. When dealing with a few counts per hour, it has been found unwise to use amplifiers and counters. A top limit of 300 counts per hour is possible with this equipment. The range of activity in common rocks and minerals is fitted to this limit by varying the source area. This is done by the use of blank aluminum discs which fill the source area except for a sector cut out to desired size, containing the sample. The discs are coated with collodion to reduce their activity, but still must be accurately measured for their background contribution.

Results--Mineral samples previously analysed for U and Th content by separate Rn and Tn determinations [HURLEY and GOODMAN, 1943], were measured for total emission in the ionization chamber. The results on 38 specimens of magnetite, four specimens of igneous rock, and one of galena are shown in Figure 2. For each sample the emission per hour per square centimeter measured by the counter minus background is plotted against the emission predicted by use of the Bragg-Kleeman rule. The points fall fairly well along the 45° slope indicating near agreement between measured and predicted values.

Repeated measurements indicated that the accuracy of the thick-source counting method is considerably higher than separate Ra-Th determinations, so that most of the scatter of the points is caused by errors in the previous work.

Samples high in thorium appear equally distributed among those high in uranium, which indicates that nothing is seriously wrong with either the present values of thorium-alpha ranges or the standards used in the Rn and Tn measurements.

The sample of galena, with more than twice the specific gravity of the samples of rock, falls into line within the scatter limits, indicating that the rule applies over a range of density covering most minerals.

Most basic rocks have nearly an equal distribution of activity between the essential minerals which makes possible an accurate calculation of the absorption factor of the rock as a whole. The calculation of μd for one of the basic rock samples (Triassic diabase) is given in Table 2 based on the chemical composition of the rock. It is usually more convenient to calculate μd from

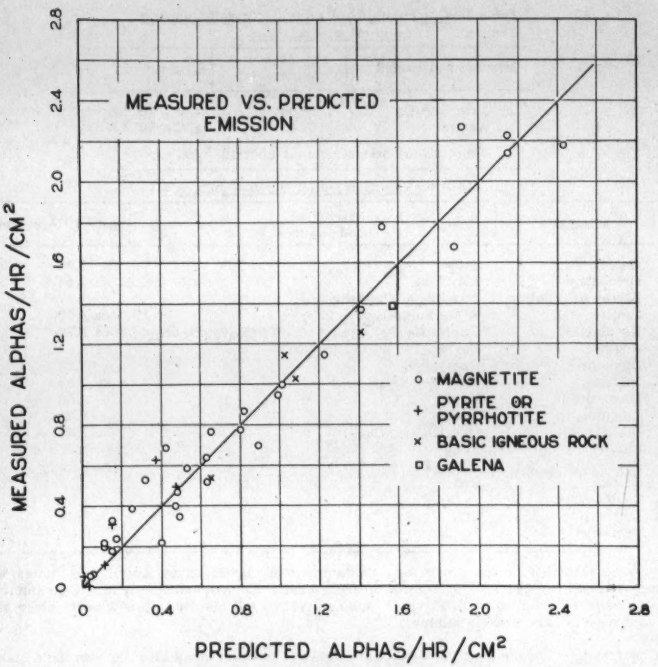

Fig. 2--Measured vs predicted emission

Table 2--Computation of μd for Triassic diabase from chemical analysis

Chemical constituent	$\Sigma f\sqrt{W}$ for each constituent	Chemical analysis	Weighted $\Sigma f\sqrt{W}$
SiO_2	4.60	0.5206	2.40
Al_2O_3	4.57	0.1573	0.73
Fe_2O_3	6.42	0.0124	0.08
FeO	6.68	0.0860	0.57
MgO	4.46	0.6530	0.30
CaO	5.67	0.1106	0.63
Na_2O	4.59	0.0219	0.10
K_2O	5.86	0.0058	0.03
H_2O	4.67	0.0050	0.02
TiO_2	5.35	0.0113	0.07
Others	...	0.0038	...
		Total	4.93

Note: $\mu d_m = (d_a/\Sigma_a f\sqrt{W})\ R f\sqrt{W} = \frac{0.001226}{3.84}(4.93) = 1.57 \times 10^{-3}$ gm/cm^3

the mineral composition as indicated on Table 3, but the results are not as accurate since the chemical composition of the minerals is not known. The other rock specimens were of about the same chemical composition, and so had very closely the same value of μd. The Ra and

Table 3--Computations of μd from Triassic diabase from mineral analysis

Mineral constituent	Per cent of mineral	μd
Labradorite	60	1.52×10^{-3}
Augite	40	1.73×10^{-3}

Thus, μd for entire rock = 1.60×10^{-3} gm/cm^3

Table 4--Values of μd for various minerals

Mineral	General composition	$\mu d \times 10^{-3}$ gm/cm^3
Quartz	SiO_2	1.48
Orthoclase	$KAlSi_3O_8$	1.54
Albite-Anorthite	$NaAlSi_3O_8$-$CaAl_2Si_2O_8$	1.47-1.54
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	ca 1.69
Hornblende	$Ca_2Na(Mg,Fe'')_4(Al,Fe''', Ti)_3Si_6O_{22}(O, OH)_2$	ca 1.72
Augite	$Ca(Mg, Fe, Al)(Al, Si)_2O_6$	ca 1.73
Diopside	$CaMgSi_2O_6$	1.55
Olivine	$(Mg, Fe)_2SiO_4$	ca 1.88
Magnetite	Fe_3O_4	2.08
Ilmenite	$FeTiO_3$	1.98
Nepheline	$(Na, K)(Al, Si)_2O_4$	ca 1.47
Pyrite	FeS_2	2.07
Pyrrhotite	$Fe_{1-x}S$	ca 2.15
Galena	PbS	4.30
Chalcopyrite	$CuFeS_2$	2.24
Sphalerite	ZnS	2.33
Hematite	Fe_2O_3	2.05

Th analyses of these four specimens were made previously by Goodman, Keevil, and Hurley, and the values used were averages of several measurements. The points representing the samples of rock are indicated by crosses in Figure 1, and are seen to fall closely in line with the other samples composed of only a single mineral.

Conclusions--The combined content of uranium and thorium in equilibrium with their disintegration series may be measured with ease and accuracy in most minerals and rocks, by a count of total alpha emission in the half space above the plane of a thick layer of the powdered sample. The chemical or mineral composition of the sample must be known and the appropriate absorption factor applied. The design of an absolute counter is described, which does not require calibration.

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PROGRESS REPORT ON SCATTERING LAYER OBSERVATIONS IN THE ATLANTIC OCEAN

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(Contribution No. 412, Woods Hole Oceanographic Institution)

Abstract--Observations with a Fathometer have shown the wide occurrence of a layer of scatterers of supersonic sound in the daytime in the Atlantic Ocean and the Gulf of Mexico at a depth of 150-250 fathoms. Other subsidiary layers are also recorded. The main layer exhibits diurnal migration in depth whose similarity to the behavior of plankton suggests a planktonic control. The behavior of the layer under various conditions, alternative hypotheses on the nature of the scatterers, and preliminary experiments to test the theory of planktonic control are discussed.

Introduction--Observations made by the Division of War Research, University of California in 1942 and 1943, showed that certain of the scatterers of supersonic sound in the ocean are horizontally stratified [UNIVERSITY OF CALIFORNIA, DIVISION OF WAR RESEARCH, 1946]. This was first demonstrated by echo-sounder records of reverberation in sea water which had a structure that could be explained only by postulating one or more layers at depths of 150 to 250 fathoms of some material capable of reflecting supersonic sound. Subsequently this group found that the more prominent scattering layers had considerable diurnal movement, staying at relatively shallow depth in the night and going deeper during the daytime. In September 1946, similar scattering layers were found by the Atlantis during a cruise from Woods Hole to Bermuda. Since that time, scattering layer observations have been carried out by the Atlantis on all her cruises. This report outlines the results obtained so far and discusses briefly some plausible explanations of the phenomenon.

Instrumentation--The Atlantis' Fathometer, which has been used for all routine observations, is keel-mounted and takes soundings by projecting vertically beamed supersonic signals at about 18 kc. A suitable scanning device records the outgoing signal and the returning bottom echo on a slowly moving strip of recording paper so that depth of water under the ship is recorded as a function of time. In usual operation the sensitivity of the receiver is set so as to record only the first echo returning from the bottom. In some places reverberations in sea water are reflected back to the receiver with sufficient intensity to record. This reverberation record generally appears as a faint continuation of the outgoing signal. Schools of fish and various other large masses of organic matter in the water are well known to give a prominent echo return on fathograms.

On September 18, 1946, just north of the Gulf Stream about 150 miles NE of Cape Hatteras, a distinct echo was recorded which became resolved from the outgoing signal five or ten minutes after sunrise and rapidly deepened to about 200 fathoms. It continued at about this depth through the daylight hours and shoaled again about a half hour before sunset. By sunset it was no longer distinguishable from the outgoing signal. Meanwhile, the bottom, which was at about 1500 fathoms, continued to be recorded. On the next day a similar record was obtained. Since that time many such records have been made of the diurnal migration of this scattering layer in different places in the western North Atlantic and in the Gulf of Mexico. Figure 1 shows three typical 24-hour records. The first two are those just described and the other is typical of the Gulf of Mexico.

Figure 2 shows that the scattering layer is definitely not a double-bottom reflection which sometimes may be recorded. It will be observed that on both records there is considerable bottom relief whereas the scattering layer in no way parallels it.

Use of the Fathometer for routine study of this type of phenomenon has the advantage that it records a very large number of signals, thus bringing out any features variable in time or any patchiness in horizontal distribution of the scattering layer. The Fathometer is moderately well suited for statistical study of the behavior of the scattering layer. However, it has several disadvantages: It allows the use of only a relatively narrow range of frequencies; its electrical spark recording feature gives only the crudest sort of data on the intensity of the received sound

and is extremely variable with the condition of the recording stylus and of the recording paper itself; as it is normally operated in deep water, it employs a rather long signal. The signal or ping length measured in equivalent travel distance in sea water is commonly 50 to 90 fathoms. Hence, the received intensity at any given instant is a summation of scattered energy from deep scatterers energized by the first of the signal and shallower scatterers energized by successively later parts of the same signal. This type of scattering record obscures much of the detail and obviously its intensity is not simply related to the density of the scatterers at any given depth. In addition, the first 50 to 90 fathoms of the record are masked by the trace of the outgoing signal.

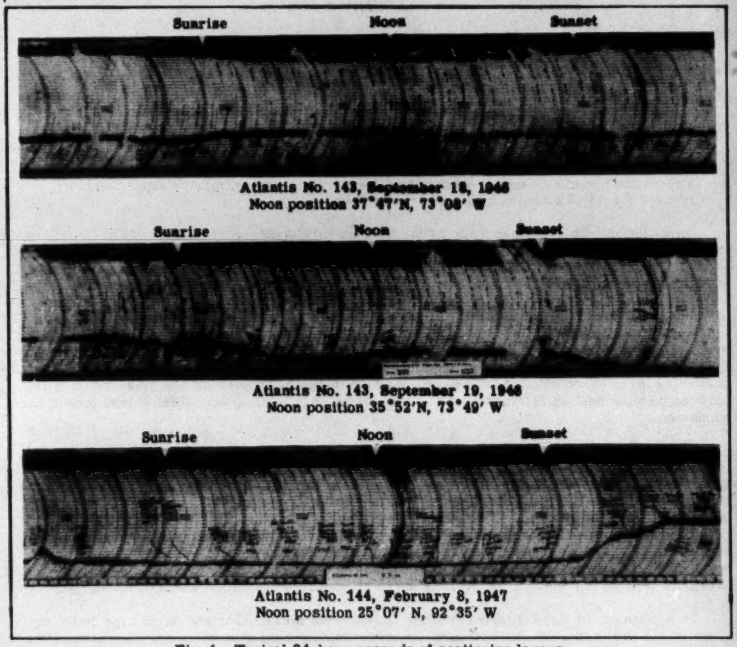


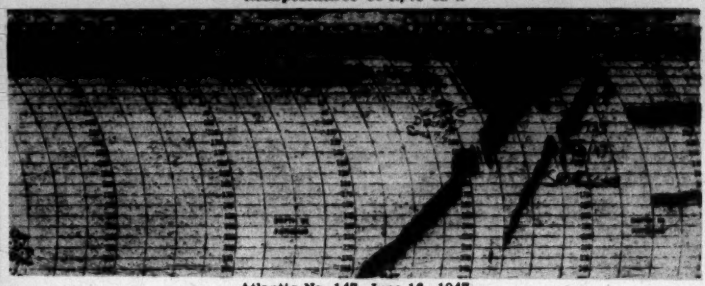
Fig. 1--Typical 24-hour records of scattering layers

By using oscillographic recording to give a faithful picture of the received intensities and a shorter signal to provide more detail, the data have been much improved. The oscillographic recording is done by photographing a cathode ray oscilloscope, connected to the output of the Fathometer's receiver. A set of oscillograms is shown in Figure 3. The oscillograms were taken of several successive signals. Note that no two oscillograms are identical, but all are similar in the general picture of the scattering layers. At the bottom of the figure is shown an oscillogram taken about the same time on the same receiver but using a small explosion as sound source. The depth relations of the peaks of scattering return are closely the same as those above. The signal length for the top oscillograms is of the order of one to three fathoms. The equivalent signal of the explosion is probably of the same order, though it may be somewhat longer.

It has been impracticable to take continuous oscillographic data throughout a cruise. However, the method has been used to study the details of the scattering layer's vertical migration at sunrise and sunset and to take correlation data during net tows. By far the bulk of scattering layer observations have been taken with the conventional Fathometer record at rather long signal lengths. Hence, the effects to be described in the balance of this report are based on this type of data,

excepting only some details of vertical migration to be described later. Plans are now being made for simple recording gear that will provide the quasi-continuous recording of the echo sounder and good reproduction of the received intensities.

Atlantis No. 147, June 14, 1947
Noon position 38°53'N, 73°52'W



Atlantis No. 147, June 16, 1947
Noon position 40°24'N, 71°13'W

Fig. 2--Scattering layer over different bottoms

Nearly all data have been taken at about 18 kc. The small amount taken at 24 kc did not differ appreciably. It will, of course, be very interesting to obtain data over a wide range of frequencies since such data should give evidence with regard to the size and nature of the scatterer. The necessary gear is now being prepared and will be used by the Atlantis in deep water soon.

Results--Since September 1946 the Atlantis has covered the area between Woods Hole, Bermuda, and the Antilles and a considerable portion of the Gulf of Mexico in various cruises. Scattering layer observations have been made on upwards of 60 days.

It now appears likely that with varying degrees of definition the main day scattering layer is present universally in deep water throughout the area studied.

The layer has generally been found to be somewhat more diffuse than on the records obtained in September near Hatteras. The types encountered are shown in Figure 4. The first is taken from the early records and looks like a typical bottom echo; the second, which is apparently weaker and more diffuse, is from the Gulf of Mexico; and the third and fourth, which are seen to be very diffuse, are from the Sargasso Sea. These are selected to show the range of definitions encountered but are not necessarily typical of the areas from which they are taken.

Analysis of all the records has been made to determine roughly the depth of the densest concentration of the scatterers at noon. It will be appreciated that in the case of a diffuse layer the

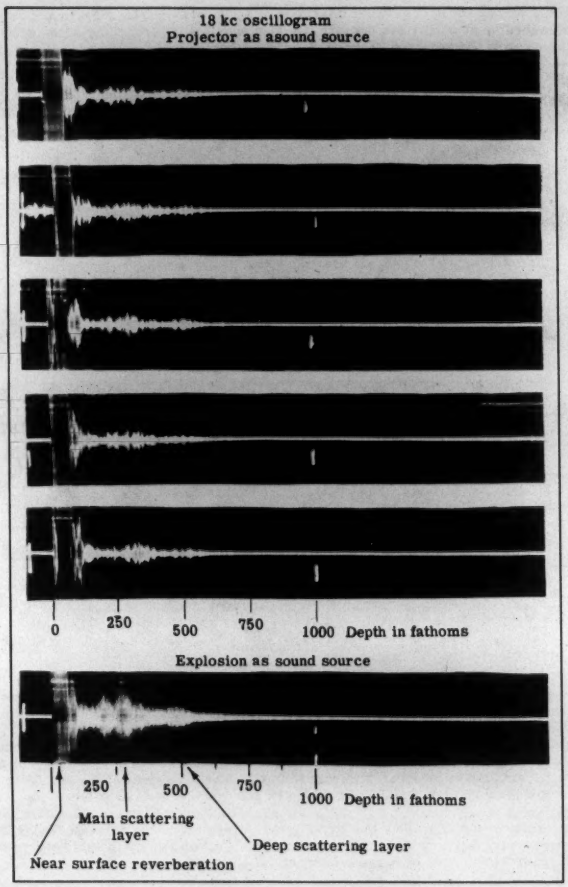
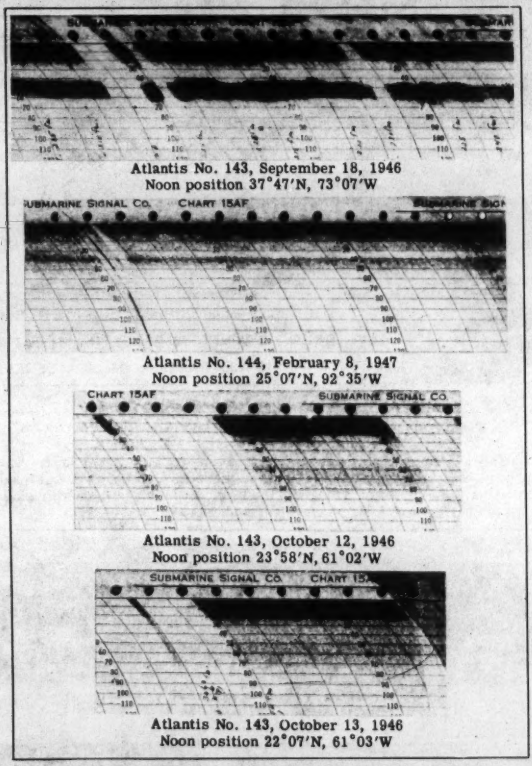


Fig. 3--Oscillograms of scattering layer

recorded sound travel times will not indicate directly the depth of scattering layer since neither its onset nor its deepest limit can be precisely distinguished. Further, the peak of reverberation will not occur precisely at the depth on the record corresponding to the depth of the densest concentration of scatterers in the ocean. This is due in part to the effect of the signal length and in part to divergence of the sound beam from its source. A crude correction has been made for these effects which is easily as good as the echo sounder data warrant. The results in noon depths of scatterers for various locations in the Atlantic and Gulf of Mexico are shown in Figure 5. The circles are noon positions at which observations were taken. The contours show the noon depths of of scatterers over the area. The overall regularity of the contours indicates this is not a random distribution of depth, but a rather regular geographic pattern.

The water at the scattering layer depth was early explored for possible gross effects such as sharp temperature or salinity changes that could reflect sound; no changes were found. This is to be expected since there are no known gross physical effects which have so regular and so large a diurnal change in the ocean. Because of the diurnal movement, the University of California group suggested that the scatterers are living organisms [UNIVERSITY OF CALIFORNIA, DIVISION OF WAR RESEARCH, 1946, p. 7]. This remains the most probable explanation and will be discussed more fully later.



Atlantis No. 143, September 18, 1946
Noon position 37°47′N, 73°07′W

Atlantis No. 144, February 8, 1947
Noon position 25°07′N, 92°35′W

Atlantis No. 143, October 12, 1946
Noon position 23°58′N, 61°02′W

Atlantis No. 143, October 13, 1946
Noon position 22°07′N, 61°03′W

Fig. 4--Examples of varying diffuseness of scattering layer

However, before discussing the possible nature of the scatterers it is well to review in greater detail what has been found about their apparent behavior in the Atlantic. First of all we have been referring to "the scattering layer." Actually, in local areas at least, there are several scattering layers and they apparently behave quite differently during any given day. The layer presented, whose depth at noon was mapped in Figure 5, is the most generally observed but there is also in some places a deeper layer that has little or no diurnal movement, and another layer which is generally slightly shallower during the day and apparently moves downward at night. Some of the evidence for these layers is shown in Figure 6. In the upper fathogram the usual layer with its daily vertical motion is evident. Its depth at noon on this day was about 200 fathoms. Another layer is seen at a depth of about 400 fathoms. Its echo is somewhat fainter, probably

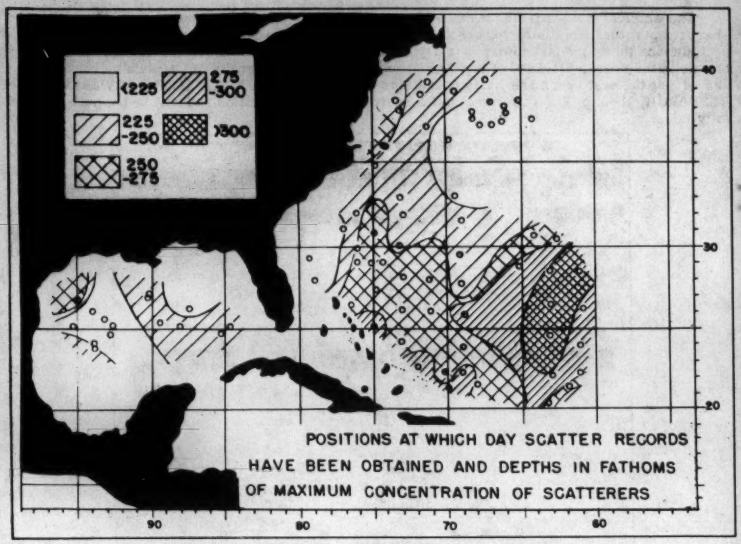
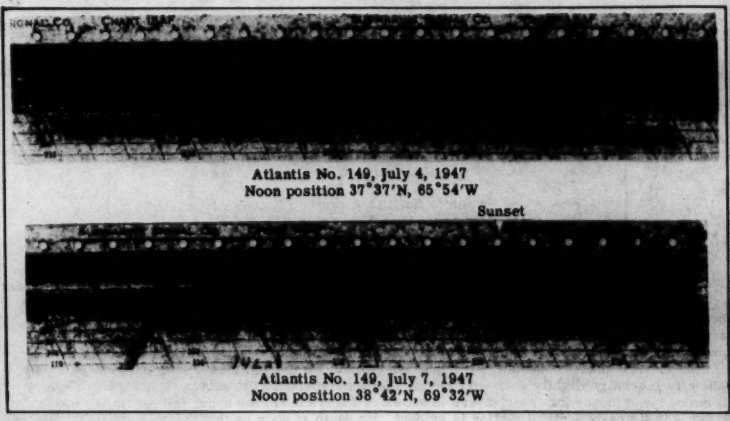


Fig. 5--Scattering layer depths, Gulf of Mexico and western Atlantic

because it is roughly at twice the depth of the other. Evidently this deeper layer, while not stationary, has no pronounced daily movement. Here it migrates downward very gradually about 50 fathoms during the day. In the lower fathogram the usual layer is again shown rising at sunset while another apparently splits off from it and moves downward.



Atlantis No. 149, July 4, 1947
Noon position 37°37'N, 65°54'W

Sunset

Atlantis No. 149, July 7, 1947
Noon position 38°42'N, 69°32'W

Fig. 6--Evening ascent of main scattering layer with other layers showing

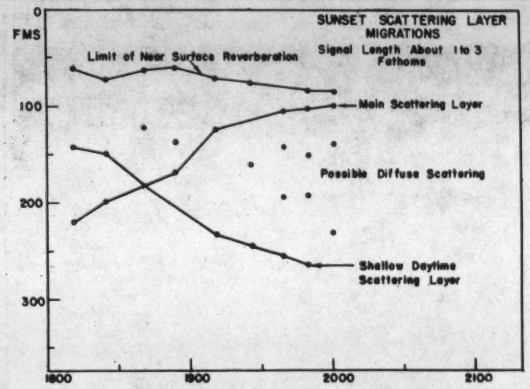


Fig. 7--Analysis of oscillograms taken about sunset, June 1, 1947 at 34°12'N, 73°30' W

This latter occurrence has been checked by short signal length records taken every ten minutes during a period from about an hour before until an hour after sunset. Analysis of the oscillograms is shown in Figure 7. Here depths of the major peaks of reverberation intensity are plotted as a function of time of day. Of course it is a matter of interpretation whether we say that the shallower layer at 142 fathoms crosses the lower one and goes deep while the deeper one shoals. The interpretation shown is made since it seems to fit more closely the large number of records obtained with long signal lengths. One point of some interest is that the two peaks shown clearly on the short signal oscillograms appear as a single broad peak on the usual Fathometer record. For this reason we have relatively meager evidence for the layer that appears to move downward at sunset. Considerably more data from short signals will be required to determine the extent of its occurrence.

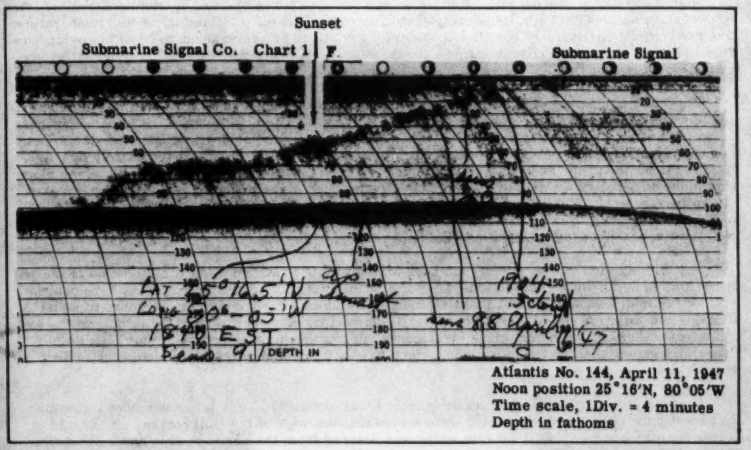


Fig. 8--Sunset ascent of a scattering layer near Miami, Florida, April 11, 1947

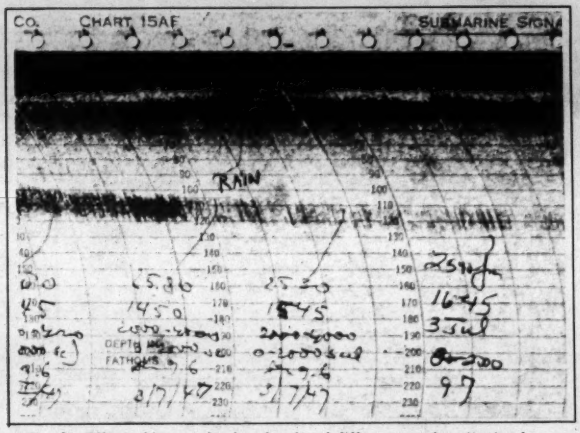


Fig. 9--Effect of heavy cloud on level and diffuseness of scattering layer; Atlantis No. 149, July 3, 1947; noon position 37°26'N, 68°15'W

Whereas the scattering layers have generally been found in water at least several hundred fathoms deep, one very striking record was obtained at sunset on April 11, 1947 in water 100 fathoms deep a few miles southeast of Miami, Florida. This is shown in Figure 8. At about a half hour before sunset a well-defined echo starts to appear just above the bottom and is seen to rise rather steadily to the surface about half an hour after sunset. In the next 20 minutes or so what appears to be the same layer is seen to sink again and become much more diffuse.

Biological correlations--The foregoing facts are the results of direct analysis of records of the Fathometer and other sound-recording instruments. Supposing that the scatterers are living organisms capable of diurnal migration let us consider the correlation of scattering layer behavior with certain factors known to influence plankton behavior. Of these, illumination and temperature are known to be particularly significant. Salinity variations are considered to be of negligible influence in the area under consideration. Temperature data are available from concurrent hydrographic observations.

The most commonly recorded scattering layer is apparently strongly affected by illumination in the water, as shown by the striking diurnal depth variation and by the effect of local heavy cloud cover. Figure 9 shows a record obtained while the Atlantis was passing through a particularly heavy rain squall. The effect of illumination has been analysed somewhat more closely by determining the depths of the recorded maximum return as a function of local apparent time and plotting these on a reference grid of illumination as a function of depth and time. Typical plots are shown in Figure 10. The illumination grid is somewhat arbitrary; it was constructed making proper allowance for Sun's altitude and the absorption coefficient for sea water in the locality. No allowance was made for variations in cloud cover or state of sea.

The illumination curves are not intended to be exact but rather to indicate the trend of diurnal variations in depth-light distribution. They are spaced 100-fold apart. These plots have proved instructive in demonstrating that the scattering layer follows the trend of the contours of equal illumination during times of rapidly changing illumination. However, during the middle of the day, a distinct flattening of the scattering layer curve occurs which suggested that some effect other than illumination might act as a barrier to further downward motion. Low temperature is proposed as a likely barrier.

That temperature changes do act as barriers was demonstrated in a number of observations taken while the Atlantis was crossing and re-crossing the edge of the Gulf Stream. Figure 11 shows such an instance. Gulf Stream water was entered from the northern side and a short time later the ship zig-zagged out of the Stream again. The fathogram shows a diffusing and deepening

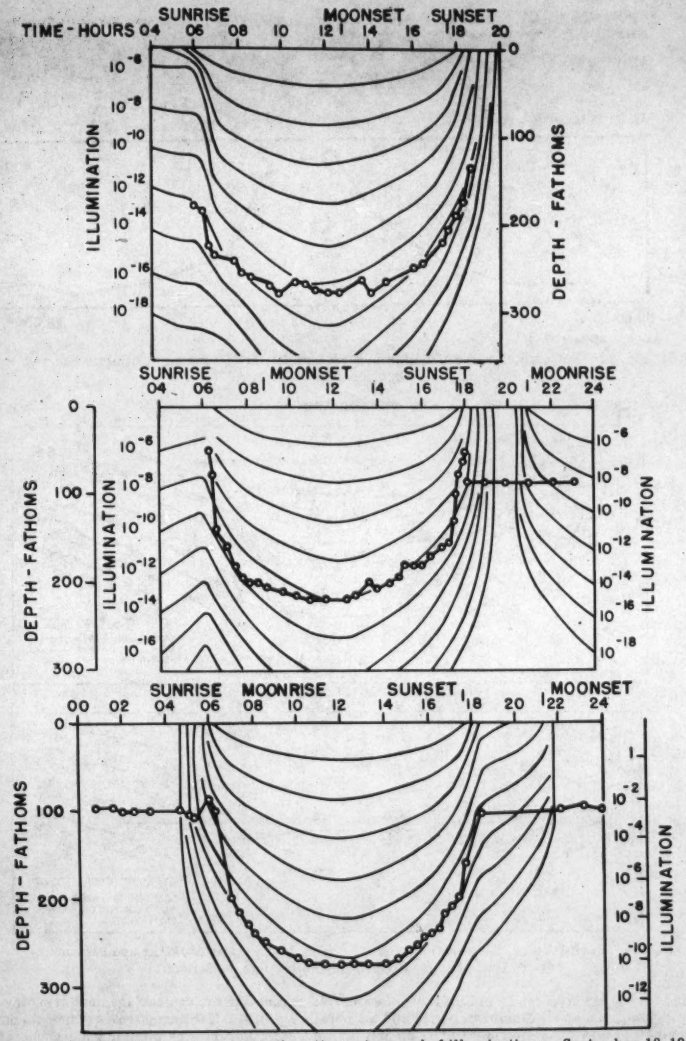


Fig. 10--(a) Diurnal variation in level of scatter return and of illumination on September 18, 1946; noon position 37°47'N, 73°08'W; (b) diurnal variation in level of scatter return and of illumination on February 8, 1947, noon position 25°07'N, 92°35'W; (c) diurnal variation in level of scatter return and of illumination on February 24, 1947, noon position 25° 26'N, 93°44'W

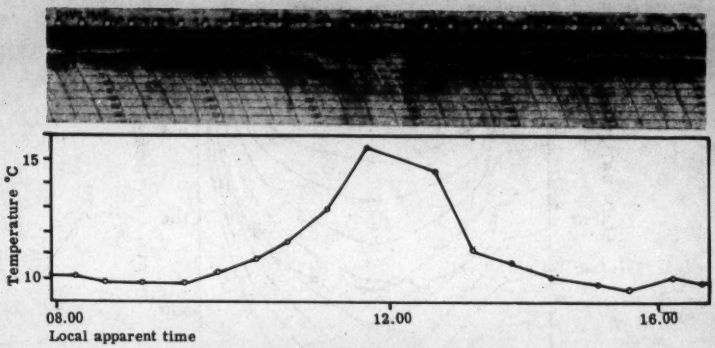


Fig. 11--Fathometer record and temperature profile at 135 fathoms; Atlantis No. 149, July 1, 1947; noon position 36°59'N, 66°57'W

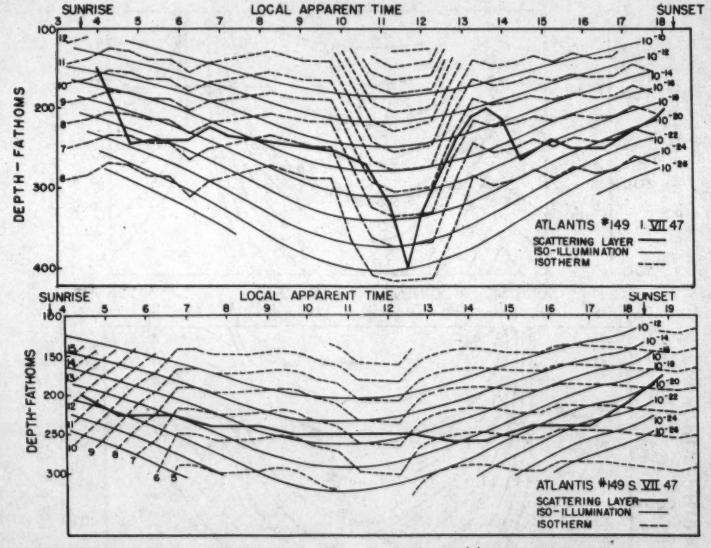


Fig. 12--Temperature, illumination, and scattering layer (a) on crossing and recrossing edge of Gulf Stream; (b) on a day entirely in colder water

of the scattering layer while in Gulf Stream water. In Figure 12a the depth of the scattering layer is superimposed on an illumination grid and temperature profile. The abrupt change in depth on entering and leaving the warm water is clearly shown. For comparison a similar record is shown in Figure 12b for a day in which the ship remained in the colder water throughout the midday period.

Figure 13 shows a record from a similar zig-zag in and out of the Gulf Stream in which the scatterer apparently disappears in the warm water and at the transition points there appears to be a greater concentration of scatterers than in adjoining cold water. An adequate explanation of this behavior must await more general knowledge of the nature of the scatterer.

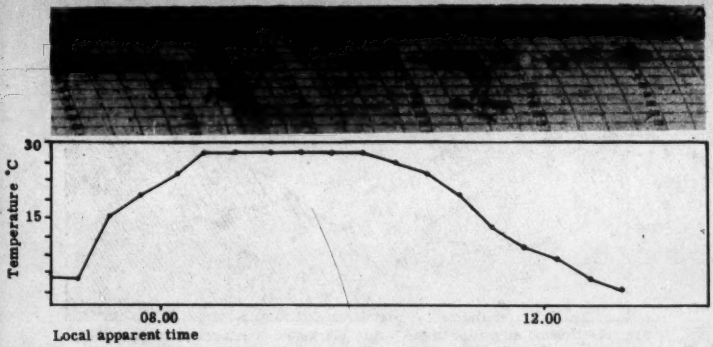
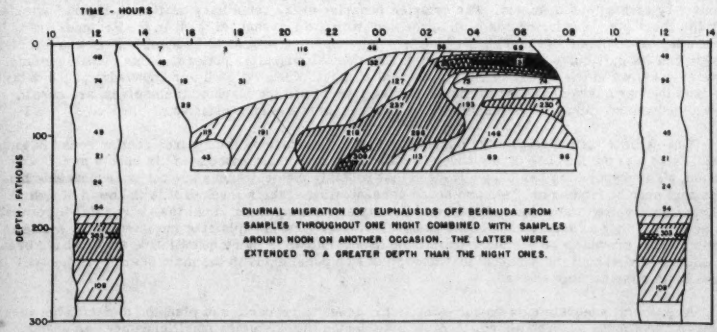


Fig. 13--Fathometer record and temperature profile at 80 fathoms; Atlantis No. 147; June 14, 1947; noon position 35°53′N, 73°52′W

Since no known physical agency could account for the characteristics which we have recorded for the scattering layer behavior, it remains to be seen to what extent a known biological agency could meet the case. Many planktonic organisms are known which exhibit a diurnal migration of the type found in the main scattering layer. A number of groups of plankton animals can be eliminated as improbable on account of their gelatinous consistency, very small size, or differing vertical distribution. Euphausid shrimps seem at present to meet the requirements best. These have a chitinised carapace. They are about an inch long, which corresponds approximately with a quarter of the wave length of sound in use on the Fathometer. They occupy the required day and night


TIME - HOURS
10 12 14 16 18 20 22 00 02 04 06 08 10 12 14
0
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DEPTH - FATHOMS
DIURNAL MIGRATION OF EUPHAUSIDS OFF BERMUDA FROM SAMPLES THROUGHOUT ONE NIGHT COMBINED WITH SAMPLES AROUND NOON ON ANOTHER OCCASION. THE LATTER WERE EXTENDED TO A GREATER DEPTH THAN THE NIGHT ONES.

Fig. 14--Diurnal migration of euphausids off Bermuda

levels as shown in Figure 14, which gives the results of a series of net hauls made near Bermuda. It should be noted that the requirements of the sampling methods have resulted in a considerable smoothing of the curves of ascent and descent in this diagram, whereas a much truer picture is obtained from the instantaneous records of the fathograms. Figure 15 shows similar results obtained further west [WATERMAN, NUNNEMACHER, CHASE and CLARKE, 1939] and includes in addition some other plankton crustacea, but gives a similar overall picture. During the course of

the present work we have, whenever possible, taken net hauls at the level indicated by the fathograms for the maximum concentration of scatterers as well as above and below this. Figure 16 shows two such hauls, one in and one above this maximum level and demonstrates clearly the concentration of euphausid shrimps in the former.

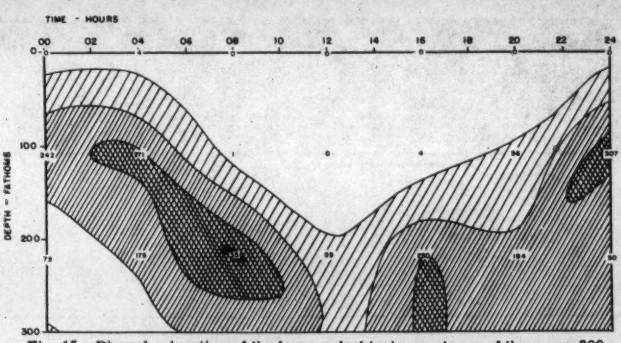

Fig. 15--Diurnal migration of the larger planktonic crustacea of the upper 300 fathoms modified from Waterman, Nunnemacher, Chase and Clarke, 1939: 39°N, 70 1/2°W

That euphausids are present in sufficient numbers is indicated by calculations made from these and other net hauls. From them it appears that a beam of sound projected from the surface to the depth of the scattering layer would suffer at least one to five per cent interception by euphausids, and probably considerably more.

From the point of view of correlation with known behavior and population density then, euphausids appear an adequate explanation of the scattering layer. As already mentioned, though, the problem is a very complicated one. Such a record as that shown already (see Fig. 8) off Miami could be taken as an ideal diagram of the evening ascent of plankton, followed immediately after sunset by sinking and diffusion. The complex behavior of the subsidiary scattering layers indicated by the short ping length records is in agreement with the fact that, at least in the Bermuda area, there is one dominant euphausid, Euphausia brevis, together with smaller numbers of other species, each with its particular vertical distribution and diurnal migration pattern. Some plankton forms even are known which appear to show a descent at night. Clearly, until our knowledge of the details of both the various components of the scattering layers, and the plankton themselves, are considerably advanced, our explanations must not be taken as more than tentative.

One serious difficulty with the hypothesis that the euphausids themselves scatter sound is their small size and the absence of any sort of swim bladder or other associated air bubble to reflect sound. The hypothesis has been advanced that possibly the scatterers are not the euphausids but fish that may be feeding on them and hence concentrating at their level. Little is known of fish populations in deep water because of the difficulty of catching them in net tows. The fish hypothesis is somewhat more attractive from the physical point of view in explaining the intensity of scatter return. If it proves to be the more promising hypothesis after more quantitative studies have been made our ideas about the size and distribution of fish populations in the main oceanic basins will have to be considerably altered.

At present, adequate data do not exist on the acoustic properties of plankton to decide between the two hypotheses outlined above. A controlled series of tests using small crustacea as sound scatterers is now underway, which, with adequate absolute sound measurements of the deep scattering layer, can be expected to clarify the nature of the scattering.

Preliminary observations have demonstrated that shrimps in moderately large quantity (of the order of 100 individuals in the sound beam at once) will reflect sound at about 20 kc at ranges of the order of six to eight feet from the projector receiver. Reasonable precautions were taken to assure that no foreign matter such as sand grains were with the shrimp and that no air bubbles stuck to them. No observations have been made at other frequencies nor has any calibration been

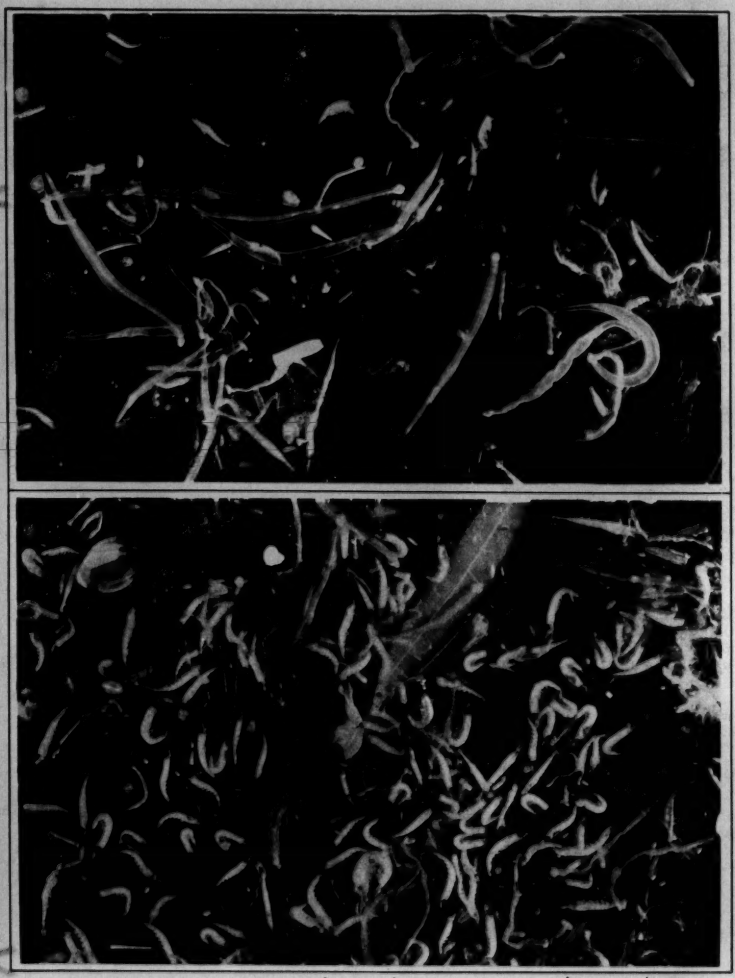

Fig. 16--Simultaneous net hauls at 29°57'N, 75°59'W; June 10, 1947; 16^h20^m to 16^h50^m L. A. T. (a) above scattering layer, 175 fathoms; (b) in scattering layer, 220 fathoms

made of the echo strength in these tests. When more quantitative tests have been made under suitably controlled conditions it will be possible to decide whether shrimp echoes can possibly account for the scattering layer data. Further controlled tests will include studies of various planktonic forms over a wide range of frequencies.

Acknowledgments--The data for this study were collected under various contracts of the Bureau of Ships of the Navy Department with the Woods Hole Oceanographic Institution. The Navy Department's permission to publish this material is hereby gratefully acknowledged. All sonic observations were made aboard the R/V Atlantis. Stanley Bergstrom and later Oakes Spalding supervised the operation, care and adjustment of the Fathometer and other sonic equipment. Valentine Worthington and Eugene Krance rigged the plankton tow nets for the hauls made with scattering layer observations. Willard Dow took many of the detailed short signal oscillographic records of the scattering layer. The cooperation of these and other members of the scientific party and of Adrian Lane, Master of the Atlantis, and his crew contributed fundamentally to the value of the data collected and is greatly appreciated.

The preliminary results presented on the reflection of sound by shrimps under controlled conditions are taken from a continuing research by Willard Dow.

Since much of the earlier work on this problem was done during World War II, we have quoted from only one paper which we know to be declassified. Omission of references to any other work that could have been included is inadvertent.

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DISCUSSION

R. H. Fleming and John Lyman (Division of Oceanography, Hydrographic Office, Washington 25, D. C.)--In addition to the report cited above, the San Diego group has issued several other reports on the scattering layer that are now unclassified [UNIVERSITY OF CALIFORNIA, DIVISION OF WAR RESEARCH, 1942, 1943, 1946a, and 1946b] copies of which are on file in the Hydrographic Office.

Three different hypotheses as to the nature of the organisms responsible for the phenomenon have now been advanced. Hersey and Moore suggest euphausids on the basis of plankton tows and their migratory habits; CHAPMAN [1947] suggested fish on the basis of the abraded tails, indicative of dense schooling, of louvar caught at about the depth of the scattering layer; and LYMAN [1948] suggested cephalopods on the basis of their known migratory habits and the abundance of their predators.

It is probable that some idea of the size of the individuals responsible for the scattering of sound could be gained by echo ranging using a narrow-beamed sound source at or near the depth of the scattering layer. In this way it should be possible to distinguish between the sound scattering caused by a large number of very small organisms, and the discrete echoes from a lesser population of larger organisms.

The recently developed techniques of underwater photography might also prove useful in identifying the organisms.

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ACTIVITY OF PARÍCUTIN VOLCANO FROM DECEMBER 1, 1947 TO MARCH 31, 1948

Ray E. Wilcox

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Parícutin Volcano, Michoacán, Mexico, completed its fifth year of activity on February 20, 1948. During this fifth year the eruption was of the same order of intensity as that of the preceding year and consisted of almost constant lava outpouring with intermittent pyroclastic activity. No symptoms of an early termination of the activity were discernible.

A record of the activity from December 1, 1947, to March 31, 1948, is shown on the diagram of eruptive characteristics (see Fig. 1), and the areas newly covered by lava are represented on the map (see Fig. 2). The reader is referred to a previous report [WILCOX, 1947] for explanatory discussion of the diagram of eruptive characteristics. Barometric pressure, tide-producing force and locally felt earthquakes are shown on Figure 1, but no comparison or interpretation will be attempted until more data has accumulated. A description of the lettered noise types is given in the first paper of this series published in the current year [WILCOX, 1948, p. 69].

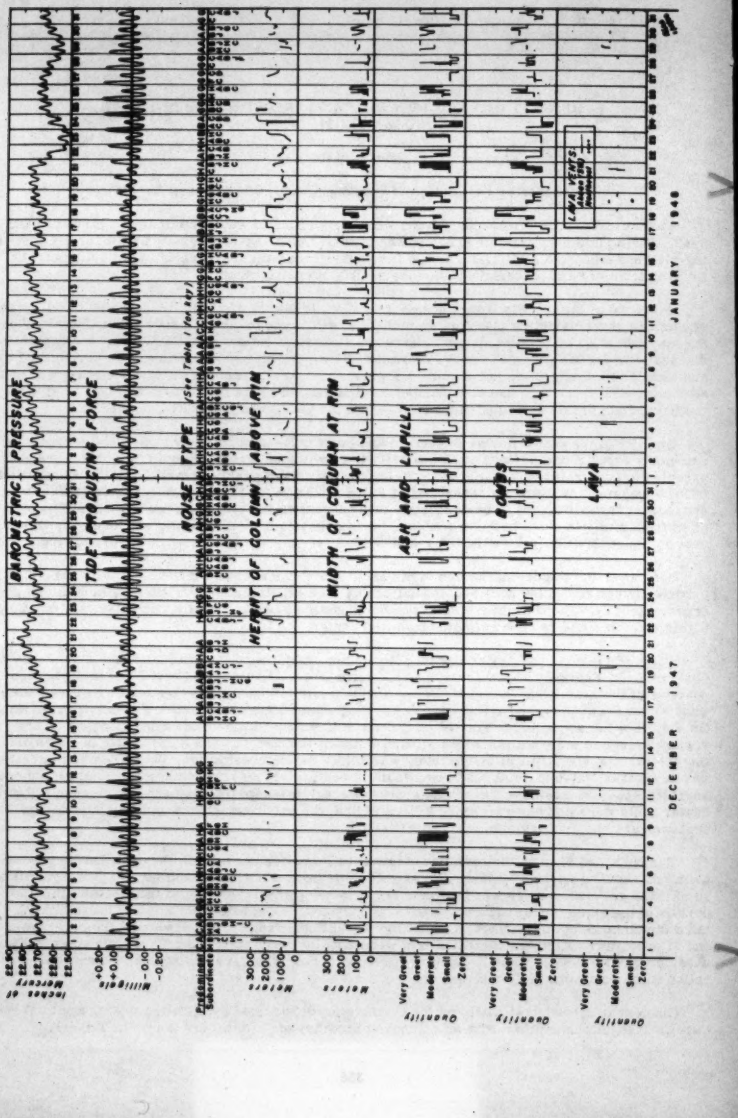
Activity of the cone--During December and January the pyroclastic activity of the cone was extremely erratic, and periods of strong activity rarely lasted more than a few hours. Frequent pyroclastic explosions took place, even during the periods of generally weak activity, and usually followed momentary complete cessations of activity. As in previous months, the variations in the eruption were too frequent to be adequately represented on the scale of Figure 1. Eruption was often from multiple vents in the crater, and on one occasion, January 8, the temporary pyroclastic vent on the southwest flank [WILCOX and SHOUP, 1948, p. 75] was active for several hours.

Soon after the opening of the new lava vent at the northeast base of the cone, February 7, the pyroclastic activity of the cone became noticeably less erratic, and the ratio of bombs to ash decreased greatly. The nocturnal displays of bomb showers became less spectacular, and on many nights no glow could be seen reflected from the crater.

Form of the cone and crater--During December and January the interior of the crater was not observed. On February 16 the crater had the form of a shallow funnel about 60 m in depth, and portions of the crater had subsided slightly inside a rim fracture. The one active vent was somewhat southwest of the geometrical center, erupting a small amount of ash and bombs at intervals. On February 20, according to Ivan Wilson, the crater was perhaps 75 m in depth, with a sharp serrated rim and steep walls. Along a NE-SW line at the bottom were three vents, of which only the central one, about five m in diameter, was active during observation. On March 11 the crater was more than 100 m in depth, and engulfment of portions of the rim had developed an even more serrated lip. Just outside the west rim a narrow crack extended partway around the cone. Two crater vents were active, again along a NE-SW line, the northeastern one emitting vapors and the southwestern one emitting ash.

Bomb-eroded rills on the cone flanks had been noted occasionally in the past, but they were not as outstanding as the regularly spaced gullies developed during December and January. About 15 of these gullies, as much as three m in depth, were gradually eroded in the steam-saturated portion of the upper northwest flank, each starting about ten m below the rim and extending one-third the distance down the flank. Coalescing depositional fans spread downward from the lower end of each gully. Although bomb showers were equally frequent on other flanks, no other gullies developed. With the decrease in quantity of bombs during February and March, the sharpness of relief of the northwest gullies decreased.

Changes in elevation of points on the crater rim, determined by alidade vertical angles from Cuseño triangulation station with an estimated accuracy of $\pm$ 1.5 m are shown in Table 1.


BAROMETRIC PRESSURE
TIDE-PRODUCING FORCE
NOISE TYPE
HEIGHT OF COLUMN ABOVE RIM
WIDTH OF COLUMN AT RIM
ASH AND LAPILLI
BOMBS
LAVA
LAVA VENTS PLUGGED
DECEMBER 1947
JANUARY 1948

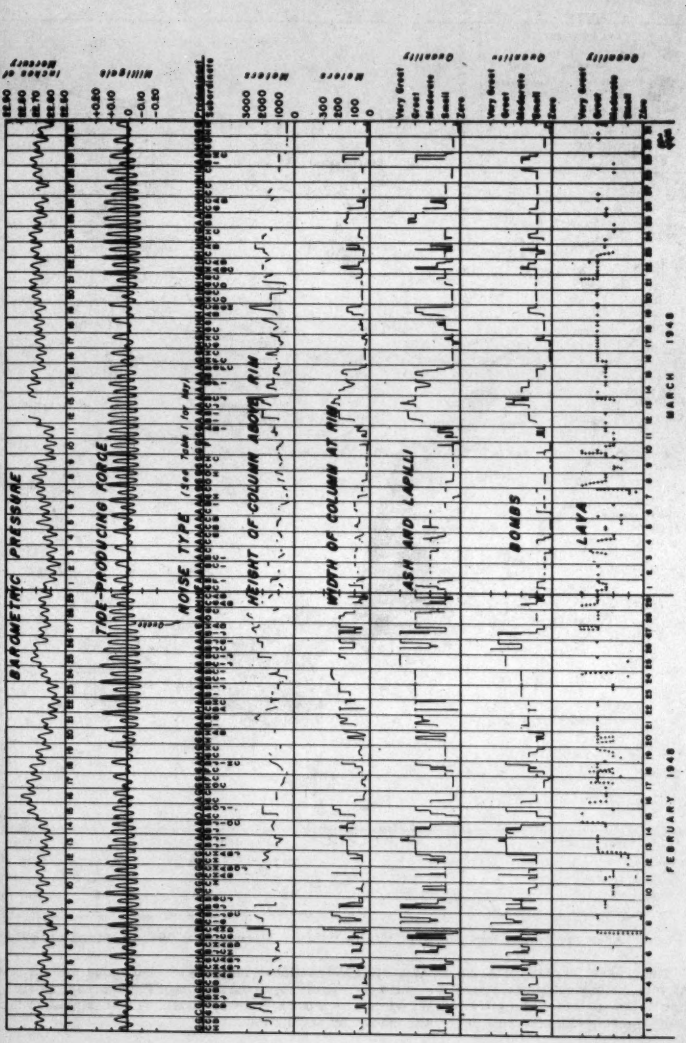


Fig. 1--Eruptive characteristics of Parícutin Volcano, December 1, 1947 to March 31, 1948

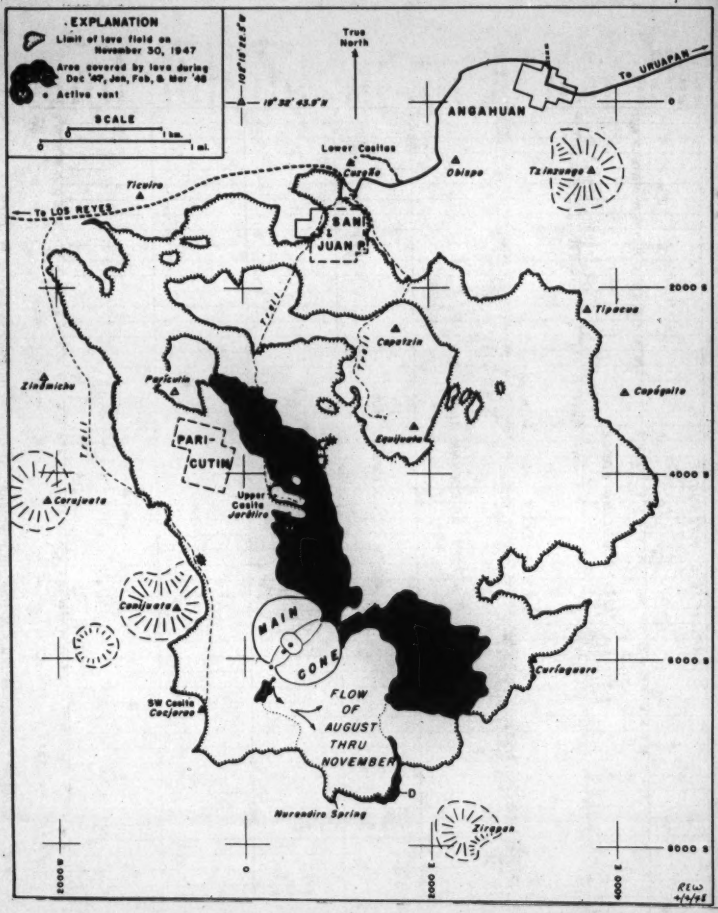


Fig. 2--Area covered by lava flows, Parícutin Volcano, December 1, 1947 to March 31, 1948

The general increase of the cone's height that had continued for many months ended in February 1948 with the beginning of a phase of engulfment. Probably about five m of the decrease in elevation of the northeast rim after January 31 can be accounted for by subsiding and sagging of the slump segment, while the remainder was caused by engulfment.

Activity of the lava vents--The rates of lava production from the vents are shown in Figure 1. The southwest lava vents, because of their position, were not as continuously observed as the northeast vent, and the quantities plotted for the evening observations of the southwest vents, being based on the intensity of reflected glow on vent vapors and clouds, cannot be as reliable as direct observations.

Table 1--Elevations above sea level of points on the crater rim

Date	West peak	Lowest point in NE rim	East peak
1947	m	m	m
November 29	2775.4	2768.9	2781.9[a]
December 31	2778.4	2768.1	2782.7
1948			
January 31	2782.9	2771.2	2787.3
February 9	...	2765.8	...
February 19	...	2751.8	...
February 29	2778.4	2751.8	2777.0
March 31	2773.2	2754.9	2775.0

[a]Incorrectly given as 2775.4 m in WILCOX and SHOUP, 1948, p. 75.

The Ahuan lava vent, most southerly of the vents shown in Figure 2, was in general strongly active up to the first part of February. Due to occasional surges of lava that flooded the vent mound, its height increased 27 m during the period August 28 to Juauary 30 and finally reached an elevation of 2672 m, only about 90 m less than that of the southwest rim of the crater. During most of this time the lava cascaded southward out of the vent mound through a persistent channel, seen at times of low activity to have a cross section about ten m wide by seven m or more deep. The Puertecito lava vent, at the immediate southwest base of the cone, was active only during the first few days in February, and the amount of lava produced was negligible. The site of the Mesa de los Hornitos vent during January cracked and swelled slightly, and hot, relatively dry vapors were emitted. Contrary to expectations, however, it was not this vent, but the vent at the northeast base of the cone that opened soon thereafter.

The opening of the northeast vent was preceded on February 6 by a renewal of subsidence between the bordering fractures of the northeast slump segment. On the evening of February 7 a pinpoint glow was noted on the northeast flank about 20 m above the site of the previous northeast vent (January-September 1947). Within a half hour the lava was cascading down the flank in large quantities but no fountaining occurred. This spot became the new lava's vent and after February 12 no activity was observed at the Ahuan vent. The northeast vent increased in elevation from time to time due to flooding, and gradually developed as a protruberance at the base of the cone. By the end of March the vent had risen 21 m to an elevation of 2584 m, or 174 m below the level of the northeast rim. On March 10 a section of the north side of the vent mound was shoved out during strong fountaining and made an outlet channel down which lava cascaded for the remainder of the month.

Activity of the lava flows--As seen in Figure 2, the flow from the Ahuan (SW) vent continued to spread widely in its northeast lobe during December, January, and February, but no movement of its southeastern lobe took place after December. This flow was notable for its great thickness

Table 2--Monthly summaries of daily weather observations, Cuzeño station

Month	Temperature		Rainfall		Ashfall		Minimum humidity	Average upper wind direction
	Max.	Min.	Total	Max.	Total	Max.		
1947	°C	°C	mm	mm	mm	mm	pct	
Dec.	22.2	2.3	78.4	26.3	7.4	1.9	38	SSW
1948								
Jan.	22.6	2.8	56.8	19.5	1.5	0.7	25	SW
Feb.	26.6	5.6	7.1	5.0	2.9	0.8	34	S
Mar.	31.9	4.9	2.5	2.5	1.2	0.6	10	SW

(about 18 m average) and its tendency to spread radially, leaving great concentric waves on its surface. The surface structure consisted of the blocky and cindery rubble normal to most Parícutin flows.

The flow from the northeast vent, starting February 7, had reached the brink of the Jarátiro-Capatzin scarp by the end of February. By March 17 it had cut the newly built trail to the Upper Casita, and at the end of March its front was advancing steadily into the "island" occupied by

Parícutin triangulation station. The thickness of this flow was normal, averaging probably less than nine m, and the surface structure was typical blocky rubble. The average rate of advance of the front was about 55 m per day, somewhat greater than normal for a Parícutin flow of this length and breadth.

Weather data--The results of daily weather observations at Cuzeño station are summarized in Table 2. The average upper wind direction expresses the direction of the wind carrying the major portion of erupted ash and vapors. Barometric pressures are shown in Figure 1.

Acknowledgments--Acknowledgment is made to Celedonio Gutiérrez for much aid in the field and for observational data during brief absences of the writer. The United States Coast and Geodetic Survey kindly furnished the computed maximum and minimum values of tide-producing force used in Figure 1.

Corrigendum--February 1948 issue, Wilcox, Ray E., and Shoup Oropeza, Samuel, Activity of Parícutin Volcano from August 1 to November 30, 1947; to the bottom of page 78 should be added: "...of the northeast vents and continued to extend its front until the middle of September. A short flow pushed northwest from the innermost vent during September."

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Washington 25, D. C.

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VON ZEIPEL'S THEOREM AND CONVECTION IN THE EARTH

Jean Verhoogen

Abstract--A theorem of astrophysics may be applied to the Earth and leads to the conclusion that the distribution of radioactive matter is probably such that the temperature is not the same at all points on a level surface inside the Earth. These differences in temperature might give rise to convection currents that circulate in meridional planes. The velocity of these currents cannot be estimated for want of data on the actual distribution of temperature, but it may be a few centimeters per year.

Introduction--The subject of convection currents in the mantle of the Earth has already been given considerable attention. Convection currents are supposed to originate either because of the existence of a super-adiabatic gradient in the mantle, or because of a zonal variation of the temperature in the substratum resulting from non-uniform heating or cooling of the crust. To these causes may possibly be added a zonal variation of temperature resulting from the distribution of radioactive matter and the ellipticity of the Earth. The probable existence of this temperature variation is suggested by a theorem of von Zeipel which we proceed first to demonstrate. The proof is that given by EDDINGTON [1932, p. 282]; we have merely replaced in his demonstration the formula for radiative heat transfer by those for transfer by conduction.

Von Zeipel's theorem--Let ϕ_0 be the gravitational potential at a point (x, y, z) in a fluid mass of density ρ. If G is the gravitational constant (6.67×10^{-8}cgs) we have, by Poisson's equation

$$\nabla^2\phi_0 = 4\pi G\rho \quad \ldots\ldots (1)$$

where

$$\nabla^2\phi_0 = \partial^2\phi_0/\partial x^2 + \partial^2\phi_0/\partial y^2 + \partial^2\phi_0/\partial z^2$$

If the mass is rotating with an angular velocity ω, the complete potential is

$$\phi = \phi_0 + \omega^2(x^2 + y^2)/2 \quad \ldots\ldots (2)$$

and

$$\nabla^2\phi = -4\pi G\rho + 2\omega^2 \quad \ldots\ldots (3)$$

For hydrostatic equilibrium we have

$$dP = \rho d\phi \quad \ldots\ldots (4)$$

and P is constant on any surface where ϕ is constant (level surface). For a homogeneous mass of given composition P is a function of ϕ alone, and $\rho = dP/d\phi$ is also a function of ϕ alone. Thus P and ρ are constant on a level surface, and consequently the temperature T is also constant on such a surface. It follows that T is also a function of ϕ alone, and all the other properties of the matter which depend only on P and T will be functions of ϕ only and will be constant on a level surface.

If k is the thermal conductivity and H the flux of heat per unit time and surface

$$H = -k\,dT/dn \quad \ldots\ldots (5)$$

where dT/dn is the temperature gradient along the normal to a level surface.

Equation (5) may be written

$$H = -k\,(dT/d\phi)(d\phi/dn)$$

and putting $k\,dT/d\phi = f(\phi)$, $d\phi/dn = -g$

$$H = g f(\phi) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Resolving H into three rectangular components

$$H_x = -f(\phi)\,\partial\phi/\partial x \qquad H_y = -f(\phi)\,\partial\phi/\partial y \qquad H_z = -f(\phi)\,\partial\phi/\partial z \quad \ldots\ldots\ldots (7)$$

Let ϵ be the amount of heat liberated per unit time and unit mass. The equation of continuity is then

$$\partial H_x/\partial x + \partial H_y/\partial y + \partial H_z/\partial z = \rho\epsilon \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Differentiating (7), we obtain

$$-\partial H_x/\partial x = f(\phi)\,\partial^2\phi/\partial x^2 + f'(\phi)(\partial\phi/\partial x)^2$$

where

$$f'(\phi) = df(\phi)/d\phi$$

and similar formulas for $\partial H_y/\partial_y$ and $\partial H_z/\partial_z$. Since

$$(d\phi/dn)^2 = (\partial\phi/\partial x)^2 + (\partial\phi/\partial\phi)^2 + (\partial\phi/\partial z)^2$$

the equation of continuity may be written

$$-f(\phi)\,\nabla^2\phi - f'(\phi)\,(d\phi/dn)^2 = \rho\epsilon$$

and combining with (3)

$$-f(\phi)[-4\pi G\rho + 2\omega^2] - f'(\phi)\,(d\phi/dn)^2 = \rho\epsilon \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Note that in (9) $f(\phi)$, ρ, ϵ, ω, are all constant on a level surface but $d\phi/dn$ is not constant unless the equipotential surfaces be spherical ($\omega = 0$). Thus (9) may be satisfied for a rotating body only if

$$f'(\phi) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

or

$$f(\phi) = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Returning to (6), (11) implies that

$$H/g = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

and (9) becomes

$$\epsilon = (4\pi GH/g)(1 - \omega^2/2\pi G\rho) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Equation (13) embodies von Zeipel's theorem. It states that the rate of liberation of heat at any point in a rotating body in hydrostatic equilibrium is given by the relation

$$\epsilon = C(1 - \omega^2/2\pi G\rho) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

where $C = 4\pi GH/g$ is a constant.

$$4\pi GH/g = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

As g is not constant on an equipotential surface if $\omega \neq 0$, (13) implies that H cannot be constant on such a surface. The flux of heat will be smaller at the equator than at the pole.

The theorem fails if $d\phi/dn$ is constant on a level surface because $f'(\phi)$, although constant, need not be 0 and H/g need not be constant.

The physical principles underlying the theorem are simple. We started on the assumption of hydrostatic equilibrium in a homogeneous body, and this assumption requires that T should be constant on a level surface where both P and ρ are constant. There must then exist a relation between the gradients of ϕ and T, and as these gradients are functions of ϵ, ρ, and ω, these quantitites must be connected somehow. More simply, the relation between ϵ, ρ, and ω, arises because the heat generated in the body tends to flow out symmetrically through a mass rendered asymmetrical by its rotation. The coincidence of the surfaces of constant temperature with those of constant potential can be achieved only if ϵ is a given function of the ellipticity of the mass.

If conditions (13) and (15) are not satisfied, then the temperature must have a zonal variation and ρ can not be constant on a surface of constant P. Hydrostatic equilibrium can no longer be maintained. Because of the symmetry of the mass, convection will occur presumably in meridional planes. The currents would rise under the poles and sink under the equator, or vice-versa, according to the manner in which the actual distribution of ϵ differs from that required by the theorem. Furthermore, because of the non-coincidence of the direction of the temperature gradient with the direction of gravity, convection would occur, provided the material has a sufficiently low strength, however small the zonal temperature variation.

Application to the Earth--It is an essential assumption of the theorem that all physical properties of the matter on a level surface should depend on P and T only, that is, the matter must be homogeneous on such a surface. The theorem does not imply that the matter should be homogeneous normal to a level surface, nor does it imply that its properties should vary continuously in this direction. Von Zeipel's theorem applies thus to any mass consisting of homogeneous concentric shells, provided its shape be that of the corresponding fluid with the same angular velocity. The theorem therefore applies to the Earth. It turns out, however, that as ω for the Earth is small (7.29×10^{-5}/sec), and as ρ varies probably between three and 15 gr/cm^3, $\omega^2/2\pi G\rho$ is of the order of 10^{-3}, and (9), (14), and (15) assume the simple, approximate forms

$$\epsilon = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

$$H/g = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

Distribution of ϵ in the Earth--Although the quantity ϵ includes the heat liberated from all possible sources, including chemical reactions, cooling, and radioactivity, we will consider mainly the latter. Equations (16) and (17) would obviously be satisfied for $\epsilon = 0$, that is, if all radioactive matter was concentrated in a negligibly thin superficial shell. This hypothesis appears now rather improbable. The ratio of the rates of liberation of radioactive heat in such extreme types of rocks as stony meteorites and granites is only approximately 1/20 [BIRCH, 1942, p. 270], whereas the mass of the mantle, not to speak of the core, is about 140 times greater than the mass of a thin crust 20 km thick; the amount of heat liberated in the mantle should thus probably be several times the amount liberated in the crust, and the hypothesis $\epsilon = H = 0$ could hardly be satisfied in the outer half of the Earth.

If $\epsilon \neq 0$, it is difficult to believe that H/g could be constant everywhere as required by the theorem, because H and g are entirely different physical quantities, depending on essentially different properties of the matter. It is hard to see, for instance, how the rate of liberation of energy at one point could be related to g which depends on the distribution of density between that point and the center of the Earth. In particular, as g is almost constant in the mantle, H would also have to be constant there, and as dT/dn probably decreases with depth, the thermal conductivity K would have to increase precisely in the manner required to keep H constant. This is a rather drastic condition which may, but is not likely to, be satisfied.

Von Zeipel's theorem is thus doubly important: If it is obeyed, it provides new equations for solving the problem of the Earth's constitution and thermal history. If it is violated, as we may assume it to be, then the Earth is not in hydrostatic equilibrium, and convection must occur.

Amplitude of zonal temperature variations--The amplitude of the zonal temperature variation depends on the difference between the actual distribution of radioactive matter and that required by von Zeipel's law. This difference is not known. We remember, however, that for a spherical mass there is no zonal variation, whatever the radial distribution of ϵ. The temperature difference between pole and equator on a level surface in a body that does not obey von Zeipel's law is thus a function of the ellipticity, and might be of the same order of magnitude as the ellipticity itself, say, 1/300. If the average temperature in the mantle is taken hpothetically as 3000°C, the average temperature difference Δ T between any point under the pole and a point under the equator at the same level might be of the order of 10°.

We may gain some indication on the maximum value of ΔT by considering the gravity anomalies which must result from an uneven zonal distribution of temperature and density. Consider a sphere of radius R in which the density at a distance a from the center varies as a function of the colatitude θ according to the relation

$$\rho = \rho_0 + \rho_1 P_2 \quad \ldots\ldots (18)$$

where ρ_0 and ρ_1 are constants and $P_2 = (3\cos^2\theta - 1)/2$.

The potential ϕ at a point situated at a distance h from the center of a sphere on a diameter through the pole is

$$\phi = \int_v (G\rho/r)dv \quad \ldots\ldots (19)$$

where

$$1/r = \sum_0^\infty [a^n/h^{(n+1)}]P_n$$

P_n being the Legendre polynomial of order n. Then

$$\phi = 2\pi G \int_0^R \int_0^\pi (\rho_0 + \rho_1 P_2) \sum_0^\infty [a^n/h^{(n+1)}]P_n a^2 \sin\theta \, da \, d\theta \quad \ldots\ldots (20)$$

Remembering that

$$\int_0^\pi P_m P_n \sin\theta \, d\theta = \begin{cases} 0 \text{ for } m \neq n \\ 2/(2n+1) \text{ for } m = n \end{cases}$$

and taking into account terms up to n = 3, we have finally

$$\phi = (4\pi GR^3/h)(1/3\rho_0 + 1/25\rho_1 R^2/h^2) \quad \ldots\ldots (21)$$

Then, at the pole where h = R

$$g\rho = -(d\phi/dh)_{R=h} = 4\pi GR(\rho_0/3 + 3\rho_1/25) \quad \ldots\ldots (22)$$

The gravity at the pole $\bar{g}_p$ for a homogeneous model of constant density would be

$$\bar{g}_p = (4\pi GR/3)\rho_0$$

and the difference $\Delta g = g_p - \bar{g}_p$ is such that

$$\Delta g/\bar{g}_p = 9\rho_1/25\rho_0 \quad \ldots\ldots (23)$$

Take Δg = 50 milligals. Then.

$$\rho_1 \approx (125/g) \times 10^{-5}\rho_0 \quad \ldots\ldots (24)$$

If the density at any level is ρ_p for $\theta = 0$ and ρ_e for $\theta = 90°$, then putting $\Delta\rho = \rho_p - \rho_e$ we find from (24)

$$\Delta\rho/\rho_m = (125/6) \times 10^{-5} \quad \ldots\ldots (25)$$

ρ_m being the mean density given by

$$\rho_m = 1/\pi \int_0^\pi (\rho_0 + \rho_1 P_2)d\theta = \rho_0 + \rho_1/4 = 1/2(\rho_e + \rho_p)$$

Now $\Delta\rho/\rho_m = -\alpha\Delta T$ where α is the coefficient of thermal expansion, so that for $\alpha = 2\times 10^{-5}$ we find finally $\Delta T \approx 10^{\circ}$. It follows that an average temperature differences of 10° from equator to pole would lead, for a spherical model, to a gravity anomaly at the pole of 50 milligals. It appears probable therefore that ΔT must be less than 10° in the Earth.

Velocity of convection currents--PEKERIS [1935] has shown that the velocity of convection currents arising from zonal temperature variations are proportional to the amplitude of the perturbation. If we assume that ΔT decreases from a maximum value of 20° at the top of the mantle to 0° at 2900 km depth, and that this decrease occurs according to one of the laws adopted by Pekeris in his calculations, then the speed would be of the order of 1/5 of those found by him, or, roughly, a few centimeters per year.

There is nothing to tell us in which direction the currents would flow, provided, of course, the stresses set up by the zonal temperature variations are sufficient to overcome the strength of the mantle. Because of the deflecting force due to rotation, it is theoretically possible that circulation would occur around the axis of revolution rather than in meridional planes; the angular speed of rotation would then become a function of latitude. Such a situation is known to exist on the surface of the Sun and is believed to be caused by departures from von Zeipel's law. It is also possible theoretically to satisfy (15) for an arbitrary distribution of ϵ by assuming that ω is a function of depth. Finally, there might be several superposed layers of circulation. Thus, no prediction may be made concerning the superficial geologic effects of the circulation. It is wished to emphasize mainly that a departure from von Zeipel's equilibrium distribution of radioactivity probably exists, and that it must lead to a non-hydrostatic state of stress in the interior of the Earth.

Author's note:--Since this manuscript was first submitted, J. Wasiutynski has published an extensive paper on Hydrodynamics and Structure of Stars and Planets [Astrophysica Norvegica, v. 4, pp. 1-497, 1946] in which he also calls attention to von Zeipel's theorem and the resulting "Eddington" currents. Wasiutynski finds that the stresses resulting from departures from von Zeipel's law would be of the order of $10^9 \Delta T$ dynes/cm^2, so that a zonal temperature variation of a few degrees would presumably be sufficient to start convection. Wasiutynski proceeds then to explain by these Eddington currents certain orogenic features of the Earth, particularly the origin of Tethys [pp. 229-240]. The reader interested in the dynamics and cooling of the Earth should lose no time in referring to Wasiutynski's very important contribution.

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PENETRATION OF RADIATION INTO THE SNOW PACK

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Abstract--A very sensitive pyrheliometer was designed and constructed by the author for measurement of the quantity of radiation transmitted through a snow pack. During March 1947, measurements of radiation transmission through the snow were made with this pyrheliometer at the Central Sierra Snow Laboratory. It was found that the detph to which radiation was transmitted increased as snow density increased. Absorption coefficients were obtained for snow between 26 and 40 per cent density. The presence of ice and slush in the snow surface resulted in a decreased albedo and increase in the amount of radiation absorbed. However, there was approximately 50 per cent reduction in the amount of radiation transmitted through the ice and slush layer to lower horizons in the snow.

The extent to which solar radiation will penetrate a snow mantle, and the effect of absorption of radiation by the snow and the soil beneath the snow on stream flow in the western states, is one of the problems being studied in the Cooperative Snow Investigations Laboratories operated by the Corps of Engineers of the Department of the Army and the United States Weather Bureau of the Department of Commerce. The Upper Columbia Snow Laboratory located near Glacier Park, Montana, and the Central Sierra Snow Laboratory near Donner Summit, California, are studying this problem.

Few measurements of the depth to which solar radiation may penetrate a snow pack have been made. HAND and LUNDQUIST [1942], using a 50-junction Eppley pyrheliometer beneath measured layers of snow near Brighton, Utah, found the depth to which solar radiation penetrated a snow pack was influenced by the physical properties of the snow. They found that the presence of ice and slush in the snow surface reduced the transmission of radiation through the snow to less than one-half of that obtained in a uniform fine grained snow. They also report that the development of one-fourth inch thickness of slush near the bottom of a four-inch layer of snow reduced transmission of solar radiation to an unmeasurable value.

Studies by GERDEL [1944] on temperature gradients in the snow pack had shown that thermohms or copper sheathed electrical resistance thermometers, occasionally indicated temperatures above 32°F at depths of ten inches in the snow. Such temperatures were attributed to the absorption of solar radiation by the thermoelectric unit since snow temperature at the same depth, as measured with small copper-constantan thermoscouples was found to be 32°F or less. Subsequent unreported experiments by the author indicated that under favorable conditions, sufficient solar radiation could be absorbed by electrical resistance thermometers at depths as great as 16 inches in the snow pack to produce erratic temperature data.

An attempt was made in the Central Sierra Snow Laboratory to measure the amount of radiation transmitted through snow with a ten-junction Eppley pyrheliometer. When connected to a recording Micromax potentiometer, having a full scale deflection of about four millivolts, the pyrheliometer was not sufficiently sensitive to measure solar radiation at depths in the snow greater than three centimeters. Using a 50-junction Eppley pyrheliometer, Hand and Lundquist apparently were not able to measure radiation through more than seven inches of fine granular snow at an elevation of 9000 ft.

It is possible that, due to the nature of their construction, the differential temperature between the hot and cold junctions of an Eppley pyrheliometer may be too small to measure accurately when buried at a depth of more than seven inches in such an effective black-body radiator as snow. Since a sufficiently sensitive instrument was not available, a pyrheliometer was designed and constructed by the writer which permitted the measurement within the snow pack of solar radiation in amounts of as little as 0.002 gm cal/cm^2/min.

This report describes the special pyrheliometer which was developed for measurement of the quantity of radiation which penetrates the snow pack. Preliminary analyses have been made of the data obtained during March 1947, with this instrument at the Central Sierra Snow Laboratory.

It is very difficult, if not impossible, to measure precisely and simultaneously all of the thermodynamic and meteorologic processes which influence snow melt. Analyses of limited data from specific experiments, such as reported in this paper, must be combined with personal observations before even tentative conclusions may be drawn. The opinions and tentative conclusions on the role of radiation in the snow melt-runoff problem presented in this paper, are those of the writer who conducted the experiments, and not necessarily those of other individuals who are associated in the Cooperative Snow Investigations.

Instrument design--The pyrheliometers used in the experiments reported in this paper consist of a square copper plate 0.02 inch thick with an exposed surface area of 40 sq cm. To the lower center of the plate a coaxial copper-constantan thermocouple was soldered. The coaxial thermocouple was constructed of a 30-inch length of 0.08 inch O. D. capillary copper tubing through which a number 30 enamel and cotton insulated constantan wire was threaded. A small drop of solder was used to close one end of the copper tube and to form the junction with the constantan wire. The coaxial construction effectively eliminated parasitic emf's which had been encountered in a previous instrument when water penetrated defective insulation on paired copper-constantan lead wires. A heater coil of number 30 constantan wire having a resistance of about 13 ohms was cemented to, but electrically insulated from, the bottom of the copper plate. Leads were provided for connecting this heater coil through a milliammeter and potentiometer to heavy duty dry batteries.

The top surface of the copper plate was given several thin coats of flat, carbon black paint. A thin coat of a dielectric black enamel was used to protect the lower surface and heater coil.

Eight coaxial thermocouples were connected through packing glands to a two-gang circuit selector switch enclosed in a moisture-proof, thermally insulated case. Four of these thermocouples were provided with the copper plates and heating coils and were used as pyrheliometers and three of the thermocouples were used to measure snow temperatures.

By means of the selector switch any one of the seven thermocouples could be connected through a galvanometer to the eighth thermocouple which was used as a reference junction.

A Leeds and Northrup model 2400-b galvanometer with integral scale and telescope was used to measure the pyrheliometer and thermocouple temperatures by deflection. This galvanometer has a coil resistance of 23 ohms and an external critical damping resistance of 80 ohms. The sensitivity of the galvanometer when used with the coaxial thermocouple was 0.058°C per division.

The pyrheliometers were installed in five-inch cubical cavities which were spaced at selected depths below a level surface in the north wall of a pit dug in the snow pack. They were supported horizontally with the surface and free of contact with the snow by suitable bending of the coaxial thermocouples. The cavities were carefully blocked with snow after installation.

The snow temperature was measured with a thermocouple inserted into the snow about three inches from the wall of the cavities in which the pyrheliometers were installed. When the top 40 cm of the snow pack was below 0°C, a pyrheliometer and a thermocouple were installed at three different depths. This permitted concurrent measurement of snow temperature and the temperature of the pyrheliometer. When the snow pack was isothermal at 0°C, pyrheliometers were installed at four depths below the snow surface. A thermocouple was inserted adjacent to the top and the lower two cavities as a means of checking on the isothermal gradient.

The reference junction was maintained at 0°C in a vacuum bottle of snow and water. The switch box, galvanometer, lead wires, and vacuum bottle were installed in the pit in the snow and were covered at all times with several layers of aluminum surfaced balloon cloth. This procedure effectively eliminated any parasitic thermal emfs.

The pyrheliometers were calibrated in the cavities in the snow by passing a measured current through the heater coil and measuring the temperature of the plate by means of the thermocouple. Calibrations were made in snow of densities between 14.5 and 44.1 per cent and at temperatures between -5.3°C and 0.0°C. During calibration the snow surface was shaded with several layers of aluminum surfaced balloon cloth.

The equation for calibration of the pyrheliometers is

$$\text{gm cal/cm}^2\text{/min} = 0.24\, I^2R\, 60/\text{area of plate sin cm}^2 \quad \ldots\ldots\ldots\ldots (1)$$

where I = amperes and R = resistance of heater coil. The calibration factor was not effected by the variations in the density or temperature of the snow pack encountered during the course of this experiment as shown in Table 1.

Table 1--Calibration of pyrheliometer

Date	Time	Snow		Current	Pyrheliometer temperature	Calibration factor
		Density	Temperature			
Feb.	h m	pct	°C	ma	°C	gm cal/cm^2/min/° C
3	13 20	20.0	0	220	5.6	0.040
3	15 28	24.3	0	80	0.8	0.036
3	15 40	24.3	0	100	1.3	0.036
3	16 00	24.3	0	148	2.7	0.041
3	16 20	24.3	0	200	4.8	0.038
3	16 40	24.3	0	250	6.7	0.043
Mar.						
5	09 30	14.5	-5.3	200	-0.3	0.037
5	10 00	14.5	-2.7	200	1.8	0.041
13	09 20	26.1	0	200	4.5	0.040
13	09 45	26.1	0	200	5.0	0.036
19	13 00	44.1	0	200	4.8	0.038

It is recognized that when installed in cavities in the snow, heat may be lost from the pyrheliometers by back radiation to the snow, by conduction through the coaxial thermocouple to the snow, and by convection induced by the temperature difference between the pyrheliometer and the snow.

The use of a measured electric current to calibrate the pyrheliometers in situ is believed to compensate satisfactorily for such loss of heat. Heat exchange owing to back radiation, convection, and conduction should be the same for like temperatures of the pyrheliometer whether induced by absorbed radiation or produced by an electric current.

The measured amount of current required to maintain the pyrheliometer at a stable temperature included that which is required to produce all heat which may be lost to the snow. The very stable temperatures obtained with this instrument indicated such heat losses were uniform.

As used in this experiment, the reaction time of the pyrheliometers, determined by stability of the plate temperature, was between two and three minutes for a change from full shade to full sunshine.

The pyrheliometers were usually installed each day at a measured depth below the snow surface adjacent to an Eppley pyrheliometer installation from which continous records of incident radiation and radiation reflected from the snow surface were obtained. Each evening, on removal, the depth of the snow layer above the cavity was again measured. The mean thickness of the snow layer was used as the thickness of snow through which the total daily amount of radiation was transmitted.

It was observed that very little change in the thickness of the snow layer above the pyrheliometer occurred before 13^h during the period of the experiments. Instantaneous measurements made previous to 13^h were considered to represent the amount of radiation which had been transmitted through a snow layer equal in thickness to that beneath which the pyrheliometers were initially installed.

On cloud-free days, measurements of transmitted radiation were made at approximately hourly intervals. On partly cloudy days, measurements were made when there was at least 20 min of unobstructed sunshine, except on March 5 when a 20-minute period of cloud-free skies did not occur.

Total incident radiation and the radiation reflected from the snow surface was measured by a pair of standard ten-junction Eppley pyrheliometers connected to recording micromax potentiometers. The pyrheliometer used to measure incident radiation was mounted on the top of a 20-foot steel tower. Reflected radiation was measured by means of a pyrheliometer mounted in an inverted position, with the target parallel to the snow surface, on an adjustable arm extending about six feet from the south side of the steel tower. This pyrheliometer was maintained at an elevation of four to six feet above the snow surface.

Results of experiments--A snow storm ending on March 4, 1947, produced several feet of low density, low-temperature snow of typical feather crystal, fluffy structure. Partly cloudy weather on March 5 maintained ambient temperatures sufficiently low to prevent important changes in the physical structure of the new snow. Short intervals of unobstructed sunshine permitted a few measurements of the radiation transmitted through this low density, cold snow. The albedo of the new snow at 12^h on March 5 was 80.9 per cent with measurable amounts of transmitted radiation observed at 30 cm below the snow surface as shown in Table 2. Of the 0.260 gm cal/cm^2/min transmitted through the snow surface, 0.193 gm cal/cm^2/min or 74 per cent was transmitted through the surface five cm of the low-density snow.

That a new fallen, low-density snow is a relatively good insulator is indicated by the comparison of transmission of radiation on March 5 with that on March 16 (see Table 2). The snow on the latter date had reached a density of 40 per cent with a coarse crystalline surface commonly characterized as "ripe" or "corn" snow.

Radiation absorbed by the coarse crystalline snow surface at 12^h on March 16 was 0.430 gm cal/cm^2/min, or 65 per cent more than the 0.260 gm cal/cm^2/min absorbed by the new snow at 12^h on March 5. Radiation transmitted to 30 cm in the 40 per cent density, coarse crystalline snow pack at 12^h on March 16 amounted to 0.026 gm cal/cm^2/min, which was 290 per cent more than the 0.009 gm cal/cm^2/min transmitted through an equal thickness of 14.5 per cent density snow at 1200^h on March 5.

Owing to the rapid change from full sunlight to almost complete overcast on March 5, the response rate of the pyrheliometers appeared to be closely approached. A slight temporary reduction in total incident radiation during the period of observation produced a proportionally greater reduction in pyrheliometer temperature at five cm than at 30 cm, below the snow surface. It is possible that a slightly different transmission gradient, although no greater depth of transmission would have been obtained under cloud-free conditions.

Despite the apparent high insulation capacity of the low-density snow, measurable amounts of radiation were observed at depths almost twice as great as measured by Hand and Lundquist with an Eppley pyrheliometer at Brighton, Utah.

Another snow storm which ended on March 10 was followed by several days of clear warm weather. An excellent opportunity was provided to study the effect of physical changes in the snow pack on the transmission of radiation. This opportunity was further enhanced by a thunderstorm on March 18 followed by a sufficient drop in temperature to produce a nine-inch coarse crust. The upper three inches of this crust had the appearance of resolidified slush while the lower six inches was of more open structure on the morning of March 19 when radiation transmission measurements were made. During most of the day the top 15 cm of the snow pack was a mixture of ice, water, and very cozrse snow crystals. Thermal quality measurements at 12^h40^m showed a free water content of 16.5 per cent in this layer.

Radiation transmission measurements in the snow pack were made on March 13, 14, 16, 19, and 20. At the beginning of this period, the top eight cm of the snow pack had a coarse crystal structure and a density of 41 per cent. Below this layer, crystal size was much smaller and density only 26 per cent on March 13.

The density of the eight to 40 cm horizon increased to 32 per cent on March 14 and 40 per cent on March 16. The increase in density was accompanied by a distinct increase in the size of the snow crystals and a visual change from a semimat to a more translucent appearance on a freshly exposed surface.

By Marcn 19 the top 60 cm of the pack had a uniform density of 44 per cent. In this horizon the upper 22 cm consisted of uniform coarse crystals. From 22 to 45 cm there was a mixture of medium and coarse crystals and from 45 to 60 cm the crystals were again uniformly coarse. The layer in which metamorphosis of the crystals apparently was not complete on March 19 was not present on March 20 when the snow pack to 60 cm depth was of uniform coarse crystal structure with a density of 45 per cent.

Although a complete series of measurements were not made on March 20, in the analysis of the data, use had been made of the fact that the percentage of incident radiation transmitted through the surface at 12^h00^m is of the same order of magnitude as the percentage of total incident radiation transmitted through the surface for the day (see Table 2).

Table 2--Penetration of radiation through snow

Date	Depth			Snow density	Radiation penetration				Remarks
					12^h00^m		For day		
	Start	End	Mean		Intensity	Portion of incident	Intensity	Portion of incident	
1947	cm	cm	cm	pct	gm cal/cm^2/min	pct	gm cal/cm^2	pct	
March									
5	0	...	0	...	0.260	19.1	...	...	Snow temperature -3.1°, feather crystal structure
	5	...	5.0	...	0.193	14.2	...	...	
	20	...	20.0	14.5	0.018	1.3	...	...	
	30	...	30.0		0.009	0.7	...	...	
13	0	0	0	...	0.390	33.0	149.2	28.2	Snow temperature 0°C, top three inches coarse crystals, thermal quality 84.6 per cent, rest of pack small crystals, open grain, thermal quality 97.1 per cent
	15	11.0	13.0	41.1	0.112	8.4	40.6	7.7	
	25	23.0	24.0	26.1	0.014	1.1	4.1	0.8	
	30	28.0	29.0		0.007	0.5	1.2	0.2	
14	0	0	0	...	0.410	30.8	157.1	29.8	Very coarse crystals top two inches, balance medium crystals close grain
	15	10.5	12.75	41.8	0.136	12.1	54.0	10.3	
	25	20.5	22.75	32.3	0.022	1.6	6.8	1.3	
	30	25.5	27.75		0.011	0.8	3.2	0.6	
16	0	0	0	...	0.430	32.4	153.3	29.4	Very coarse top four inches, medium to coarse crystals below
	15	11.0	13.0	41.7	0.151	11.4	51.7	9.9	
	25	21.0	23.0		0.035	2.7	8.3	1.6	
	30	26.0	28.0	39.7	0.026	2.0	6.3	1.2	
	40	37.0	38.5		0.011	0.8	2.9	0.6	
19	0	0	0		0.530	37.8	220.2	38.4	Very coarse ice crust to three inches, moderate crust to nine inches after rain on March 18; very wet at 12^h; thermal quality 83.5 per cent top three inches
	15	10.0	12.5		0.099	7.1	34.8	6.1	
	25	19.0	22.0	44.1	0.026	1.9	10.0	1.7	
	30	26.0	28.0		0.013	0.9	5.9	1.0	
	40	35.0	37.5		0.004	0.3	2.2	0.4	
20	0	0	0	...	0.500	36.3	...	...	Snow covered with paper and canvas during night to prevent freezing; dry but friable in morning
	7.5	...	7.5		0.242	17.4	...	...	
	16.0	...	16.0	44.8	0.088	6.3	...	...	
	22.0	...	22.0		0.046	3.4	...	...	
	32.0	...	32.0		0.015	1.1	...	...	

Plotting the percentage of total-incident radiation for the day transmitted through the snow on March 13, 14, 16, and 19 and the percentage of incident radiation per minute transmitted through the snow for the $12^{h}00^{m}$ observation on March 20, Figure 1 indicates that radiation is transmitted to increased depths as snow density increases.

As pointed out by Hand and Lundquist, radiation absorption in the snow may be expected to follow a law somewhat like that for distilled water

$$I = I_0 e^{-kd} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where I_0 is the intensity of radiation transmitted through the surface of the snow, I the intensity at depth, d and k is the absorption coefficient for snow. The value for k, determined by Eckel, is reported by HAND and LUNDQUIST [1942] to be about 0.083.

IDUMI [1936], using a dark-wedge photometer obtained a transmissibility value of 0.883 for snow, equivalent to an absorption coefficient of 0.117.

Using a photoelectric cell which was sensitive only at 0.3 to 0.7 μ, OLSSON [1936] obtained a mean value for k of 0.074. With an Angstrom pyranometer, an instrument similar to an Eppley pyrheliometer, he obtained a value of 0.114 for the coefficient of absorption of radiation by snow.

A photoelectric cell, although highly sensitive in the luminous or visible wave lengths, is practically insensitive to the infrared or heat wave lengths longer than 0.7 . Since more than 50 per cent of the solar energy received at the snow surface is in wave lengths longer than 0.7 μ, a photoelectric cell will not give a direct quantitative measurement of radiation transmission in snow.

Olsson indicates that absorption of radiation may be influenced by the character of snow, such as variations in crystal structure and density.

Equation (2) may be applied at any intervals of depth in the snow, where I_0 is the amount of radiation transmitted through a plane at any depth, I the amount measured at any depth below this plane, and d the depth interval. This permits the determination of k for a horizon of snow of any density in a snow pack of variable density where transmitted radiation is measured at two or more planes within the stratum of uniform density

Equation (2) may be expressed as

$$k = (\log_e I_0 - \log_e I)/d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Applying (3) to Figure 1 for strata of measured density in the snow pack, the values shown in Table 3 were obtained for the absorption coefficient.

Table 3--Values determined for the absorption coefficient

Density	k
pct	
26.1	0.280
32.3	0.184
39.7 }	
44.8 }	0.106

It appears that the radiation absorption coefficient of a snow pack is a function of the snow density, at least for snow of the monohexagonal, fine to coarse crystal structure.

Discussion--It has been recognized by hydrologists that critical discharge from the snow bearing areas of a basin is associated with a snow pack density of 40 to 50 per cent. The part that solar radiation plays in the conversion of a low density snow to a pack of high density is well illustrated in Figure 1. On March 13 the top 15 cm of the pack was already at 40 per cent density and the radiation absorption coefficient for that portion of the pack was low, indicative of a high transmission capacity. The lower portion of the pack was at 26 per cent density and had a high absorption coefficient, indicative of a low transmission capacity. As the density of the snow pack below 15 cm increased the absorption coefficient decreased and the transmission capacity and depth of absorption increased. By March 16 the snow, to a depth of 40 cm, had reached a uniform density of about 40 per cent with a constant absorption coefficient of 0.106 throughout that depth. The larger amount of radiation absorbed in the low density snow during this period appears to have been a material source of any energy required to convert the fine grain, low density snow to a coarse crystal, high density snow.

It is apparent that free water in the upper 30 to 50 cm of a snow pack may absorb radiation and, as it percolates downward, carry heat to lower depths in the pack. Such a process may contribute to the development of a coarse crystal, high density snow pack of considerable depth.

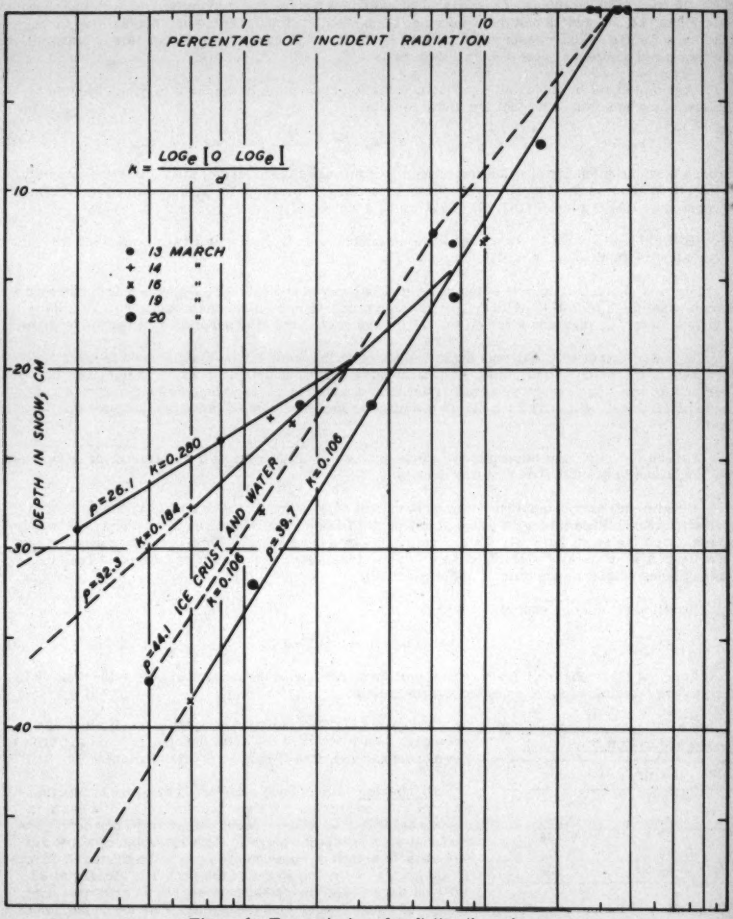

Figure 1--Transmission of radiation through snow

The absorption and transmission of radiation appears to be a self-accelerating process which may have a considerable influence upon any runoff-degree-day factor. For any degree-day unit, more runoff might be expected during clear weather from a high density snow pack with a low radiation absorption coefficient than from a low density snow with a high absorption coefficient. The radiation absorbed by a low density snow appears to be used as a source of energy for physical and structural changes in the crystal matrix rather than for the production of dischargeable water. There is less opportunity for the radiation transmitted to the greater depths in high den-

sity snow to be lost by upward diffusion and back radiation from the snow surface at night and the diurnal accumulation of radiant heat may accelerate the rate of discharge from a high density snow pack.

The effect of ice and slush within the surface nine inches of the snow pack on radiation transmission is shown in Table 2 and Figure 1. The dense ice surface to three inches and heavy crust to nine inches on March 19 which became very wet at 12^h and which was not completely disintegrated until 15^h reduced the amount of radiation transmitted to all depths below the surface at 12^h to less than 50 per cent of that transmitted on March 20 when the snow surface had been well protected from freezing and almost all free water had drained out during the previous night.

Transmission of radiation through the ice and slush layer, shown by the dotted line in Figure 1, indicates that the low absorption coefficient, characteristic of a high density snow pack, applies to all depths in the pack below the ice and slush layer. The decrease in total radiation transmitted to deeper portions of the pack through a 15 cm ice and slush layer has been more than offset by the great increase in that absorbed within that layer during the day as shown in Table 2. An albedo of 61.3 per cent, Table 4, for the ice and slush snow surface was the lowest obtained during the course of this experiment. The total radiation of 220 gm cal/cm^2/day, absorbed at the surface of the ice and slush layer was 40 per cent higher than that absorbed by the snow surface on any other day during the course of these experiments.

Table 4--Incident radiation and radiation reflected from the snow surface

Date 1947	12^h00^m			Total for day		
	Incident	Reflected	Albedo	Incident	Reflected	Albedo
March	gm cal/cm^2/ min	gm cal/cm^2/ min	pct	gm cal/cm^2	gm cal/cm^2	gm cal/cm^2/ min
5	1.36	1.10	80.9	...	...	...
13	1.33	0.94	70.7	529.4	387.2	73.1
14	1.33	0.92	69.2	526.4	369.3	70.2
15	1.33	0.91	69.2	...	...	...
16	1.33	0.90	67.7	521.0	367.7	70.6
19[a]	1.40	0.87	62.1	574.0	353.8	61.3
20	1.39	0.89	64.1	...	...	...

[a]Rain as thunderstorms afternoon of March 18; dense ice crust three inches deep with more friable crust to nine inches on morning of March 19; top three inches was a very wet, coarse, crystal slush at 12^h which did not dry out until 15^h.

It is apparent that low ambient temperatures, or appreciable long wave back radiation from the snow surface may produce an ice layer, and subsequent absorbed radiation may produce a mixed ice and slush layer on the snow surface either of which may retard, but will not stop the process of radiation transmission into the snow pack. The high radiation absorption capacity of the ice and slush surface causes a fairly rapid disintegration of such layers. With an ice layer at or close to the freezing point, as much water may be produced, by the absorbed radiation as would have been produced in the entire horizon by an equal amount of radiation transmitted to lower depths. As soon as the ice planes are disintegrated, the temporarily stored, free water in the ice and slush surface may be discharged through the snow pack. The lower albedo associated with the ice or slush surface may result in sufficient increased absorption of radiation to offset any previous cooling of the snow surface below the freezing point, and may even produce increased amount of melt water on cloud-free days.

There may be sufficient intervals of clear weather between small storms during the winter to permit the development of an extensive horizon with a low radiation absorption coefficient. If a small storm does not produce more than 20 inches of snow, this increment may be completely converted to high density snow by absorbed radiation before the next precipitation period. When four to six ft or more of snow are deposited in a single storm, the increase in density below 20 inches in such a pack is dependent upon heat transfer by conduction, percolating water, and compaction. During the winter months when ambient temperatures are low and night-time back radiation offsets day-time absorbed radiation, there may be little or no positive heat balance available for transfer to lower depths. Any increase in the density of a deep snow pack resulting from several large storms above that produced in the surface 20 inches by absorbed radiation and by settling, will be delayed until such time as sufficient heat from warm rain, absorbed radiation or high ambient temperatures become available for conduction to depths below that to which appreciable amounts of radiation may be transmitted.

It would appear that a deep snow pack produced by frequent small storms, interspersed with intervals of clear weather, may have a high density near the end of the snow season. On the other hand, a snow pack of similar water equivalent produced by a few very large storms may be of low density near the close of the season. Earlier and more rapid spring discharge may be expected from a snow pack produced by a series of small storms than from a pack produced by a few large storms, other conditions being equal.

The transmission of radiation through a shallow snow mantle to the underlying soil may have a marked influence on runoff from melting snow or from rain on snow.

On the west slope of the Sierra, a storm may leave a snow cover down to an elevation of 3000 ft or even lower. This snow cover usually recedes to 4000 ft or higher with a few days. If the storm has been preceded by cold weather the snow may fall on a frozen soil.

The snow blanket protects the soil surface from further freezing thus permitting some thawing by conduction of heat from lower depths in the soil. An even larger amount of heat may be absorbed by the soil surface from radiation transmitted through the shallow snow mantle. One inch of frozen soil surface, having a water content of 40 per cent by volume can be thawed out in two days beneath a six-inch snow mantle of 26 per cent density by transmitted radiation alone. In the Sierra the frozen soil surface seldom exceeds one inch in depth and usually it is no greater than one-half inch thick in the transitional zone between elevations of 2500 and 4500 ft. Even at the lower elevations, snow apparently undergoes definite physical changes and a considerable increase in density before appreciable discharge takes place. The underlying frozen soil may be entirely thawed out during the period in which the snow mantle undergoes these critical changes with a resultant increase in permeability and reduction in peak or total discharge from the melting zone. Where sufficient antecedent and current information are available the hydrologist may give due weight to the effect that radiation may have on storm runoff from portions of snow covered basins within this critical melting zone.

The study of radiation absorption be the snow pack will be extended in the Cooperative Snow Investigations Laboratories to cover a wide range of climatological and snow pack conditions. When sufficient data becomes available a complete report on this project will be prepared.

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QUALITY OF WATER IN THE UPPER COLORADO RIVER BASIN

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In a drainage area as large as the Colorado River Basin there are naturally large differences in the quality of the surface waters. The chemical character of the water at six gaging stations on the Colorado River from near the headwaters to near the mouth is shown by the analyses in Table 1.

Table 1--Quality of the water at six gaging stations on the Colorado River

Item	Colorado River between Hot Sulphur Springs and Grandby, Colorado, August 1, 1946	Near Glenwood Springs, Colorado; sampled at Shoshone Dam; weighted average for year, 1944-1945	Near Cameo, Colorado; sampled at Grand Valley Diversion Dam; composite for period shown, August 11-20, 1945	Near Cisco, Utah; composite for the period shown April 11-14, 17-20, 1946	Near Grand Canyon, Arizona; weighted average for year, 1944-1945	Yuma Main Canal below Colorado River siphon; weighted average for year, 1944-1945
	ppm	ppm	ppm	ppm	ppm	ppm
Silica (SiO_2)	. . .	10	10	13	14	11
Iron (Fe)	. . .	0.07	. . .	. . .	0.19	0.04
Calcium (Ca)	15	38	53	72	90	91
Magnesium (Mg)	2.8	8.5	13	23	28	29
Sodium (Na)	6.4	31	60	78	93	99
Potassium (K)		2.5			8.5	5.3
Bicarbonate (HCO_3)	68	95	129	183	224	163
Sulfate (SO_4)	3.5	58	95	207	251	300
Chloride (Cl)	2.0	42	78	54	78	82
Fluoride (F)	. . .	0.2	. . .	. . .	0.3	0.3
Nitrate (NO_3)	1.1	0.5	1.0	3.0	2.2	1.5
Borate (BO_3)	. . .	0.1	. . .	. . .	0.3	0.4
Dissolved solids						
Parts per million	64	238	374	540	676	699
Tons per acre-foot	0.09	0.32	0.51	0.73	0.92	0.95
Specific conductance ($K \times 10_5$ at 25°C)	12.3	40.2	63.9	83.4	98.9	107
Hardness as $CaCO_3$						
Total	49	130	186	274	340	346
Noncarbonate	0	52	80	124	156	212
Per cent sodium	22	34	41	38	37	38

It will be seen that the concentration of dissolved solids increased from 64 ppm (0.09 tons per ac ft) in the headwaters to 699 ppm (0.95 tons per ac ft) near the mouth.

The quality of the water in the main stream is influenced by the quality of the water in its tributaries. The chemical character for three direct tributaries to the Colorado River (Gunnison, Green, and San Juan Rivers) is shown by the analyses in Table 2.

Table 2--Quality of the water in streams tributary to the Colorado River

Item	Green River at Green River, Utah; weighted average for year 1929-1930	Gunnison River near Grand Junction, Colorado; composite for period shown, July 11-20, 1945	San Juan River near Blanco, New Mexico; composite sample for period shown, May 21-25, 27-31, 1946	San Juan River at Ship Rock, New Mexico; weighted average for year, 1944-1945	San Juan River near Bluff, Utah; weighted average for year 1944-1945	Animas River at Farmington, New Mexico; weighted average for year, 1944-1945
	ppm	ppm	ppm	ppm	ppm	ppm
Silica (SiO_2)	14	16	15	14	12	7.7
Iron (Fe)	0.13	...	0.09	0.09	0.16	0.05
Calcium (Ca)	59	98	22	47	71	55
Magnesium (Mg)	23	34	4.6	10	17	9.0
Sodium (Na)	56	70	14	34	49	19
Potassium (K)	3.8					
Bicarbonate (HCO_3)	179	163	77	115	167	118
Sulfate (SO_4)	177	371	36	120	187	101
Chloride (Cl)	26	10	2.5	9.0	13	9.5
Fluoride (F)	...	...	0.3	0.3	0.4	0.3
Nitrate (NO_3)	1.2	3.2	0.5	1.5	2.5	0.9
Borate (BO_3)	...	...	0.1	0.2	0.3	0.1
Dissolved solids						
Parts per million	448	682	133	293	434	261
Tons per acre-foot	0.61	0.93	0.18	0.40	0.59	0.35
Specific conductance ($K \times 10_5$ at 25°C)	...	96.0	20.8	43.9	64.8	41.0
Hardness as $CaCO_3$						
Total	242	384	74	158	247	174
Noncarbonate	95	251	11	64	110	78
Per cent sodium	33	28	30	32	30	19

It will be noted that the dissolved solids in the Gunnison River are more concentrated than in the Green and San Juan Rivers. The average concentrations for the Green and San Juan are about equal, and slightly less than the average concentration for the Colorado River at Cisco (see Table 1). Analyses for three stations on the San Juan (see Table 2) show a progressive downstream increase in dissolved solids. The concentration of dissolved solids in the Animas at its mouth (see Table 2) is about equal to the concentration in the San Juan at Ship Rock, a few miles below the mouth of the Animas.

Only a few records are avilable for Green River above Green River, Utah, but it appears that the concentration of dissolved solids in the Green River also show a progressive downstream increase.

These increases are caused chiefly by natural ground-water inflow into tributaries and the main stream and return wastes from industrial and agricultural developments. In some short stretches of the river the increases are rather large, for example, in the stretch of river near Grand Junction, Colorado (see Table 3).

The analyses of river water show the increase in dissolved solids for this stretch, indicating inflow of water with high mineral content. The analysis of the drain water (see Table 3) represents a water of high mineral content which is probably more concentrated than most of the water entering the river in this stretch.

Table 3--Quality of the water in the Colorado River and a drain near Grand Junction, Colorado

Item	Colorado River near Cameo, Colorado above Grand Valley Diversion Dam, December 8, 1934	Colorado River at Grand Junction, Colorado, sampled at highway bridge, above mouth of Gunnison River, December 8, 1934	Drain in the Grand Valley project near Loma, Colorado, December 8, 1934
	ppm	ppm	ppm
Silica (SiO_2)	15	14	16
Iron (Fe)	0.04	0.04	0.05
Calcium (Ca)	118	145	522
Magnesium (Mg)	31	66	434
Sodium (Na)	44	290	855
Potassium (K)	5.6	6.4	14
Bicarbonate (HCO_3)	239	256	388
Sulfate (SO_4)	270	565	4054
Chloride (Cl)	348	320	241
Fluoride (F)	0.1	0.3	0.0
Nitrate (NO_3)	2.0	20	72
Borate (BO_3)	...	...	...
Dissolved solids			
Parts per million	1151	1553	6400
Tons per acre-foot	1.57	2.11	8.70
Specific conductance ($K \times 10_5$ at 25°C)	...	...	...
Hardness as $CaCO_3$			
Total	...	...	...
Noncarbonate	...	...	...
Per cent sodium	56	50	38

The concentration and chemical character of dissolved solids in most streams vary considerably throughout the year and, as a rule are more concentrated during periods of low flow and have the minimum concentration of dissolved solids during flood periods. The range for the Colorado River above Glenwood Springs, Colorado, and below Boulder Dam, during one year are shown in Table 4.

In unregulated flow, the range in concentration of dissolved solids may be very large. During storage in a large reservoir the incoming water mixes with the reservoir water and, as a result, releases from a large reservoir rarely show large fluctuations in mineral content. This uniformity in concentration is shown by the analyses for the Colorado River below Boulder Dam (see Table 4). Comparison of these analyses for Boulder Dam and the one for the Colorado River at Grand Canyon, above Boulder Dam (see Table 1) shows a slightly higher calcium, sulfate, and dissolved solids and a lower bicarbonate at Boulder Dam. These increases were caused by solution of reservoir deposits and through concentration because of evaporation from the reservoir. It is likely that the changes through solution observed at Boulder Dam during the past few years were greater than will be found in future years. The rates of evaporation and subsequent changes in concentration will probably be less in reservoirs in the Upper Basin than have been observed at Boulder Dam.

There are few processes which will benefit the quality of surface waters and it is apparent that the best quality waters in the Colorado River Basin are in the Upper Basin. Use of the water

Table 4--Quality of the water in Colorado River at Glenwood Springs and at Boulder Dam

Item	Shoshone Dam near Glenwood Springs, Colorado, June 1-10, 1942	Shoshone Dam near Glenwood Springs, Colorado, January 1-10, 1942	Below Boulder Dam, November 21, 23-27, 29, 30, 1941	Below Boulder Dam, June 11-12, 15, 19-20, 1942
	ppm	ppm	ppm	ppm
Silica (SiO_2)	11	15	12	13
Iron (Fe)	0.15	0.02	0.02	0.04
Calcium (Ca)	22	73	98	104
Magnesium (Mg)	4.1	17	24	28
Sodium (Na)	6.2	107	89	97
Potassium (K)	1.3	4.2	5.3	8.7
Bicarbonate (HCO_3)	69	157	147	161
Sulfate (SO_4)	19	132	312	340
Chloride (Cl)	6.5	157	67	75
Fluroide (F)	0.3	0.2	0.4	0.3
Nitrate (NO_3)	0.5	1.0	3.0	2.8
Borate (BO_3)	0.1	0.2	0.5	. . .
Dissolved solids				
Parts per million	105	584	683	748
Tons per acre-foot	0.14	0.79	0.93	1.02
Specific conductance ($K \times 10_5$ at 25°C)	17.1	100	104	111
Hardness as $CaCO_3$				
Total	72	252	343	374
Noncarbonate	16	124	222	242
Per cent sodium	17	49	37	37

for irrigation and subsequent return to the stream of drainage waters will cause an increase in the dissolved solids content of the river water. The increase in dissolved solids is often largely in the sodium salts which may influence greatly the value of the river water for further irrigation use. Storage of water in a large reservoir will produce water of relatively uniform mineral content and this may be of material benefit to downstream users. This is particularly true for those users who normally would be taking large volumes of water from the river during periods of more highly mineralized water.

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QUALITY OF WATER IN THE NORTHWEST

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The quality of natural waters, as judged by the dissolved mineral content, is quite varied throughout the Northwest. The concentrations of dissolved solids range from less than 50 ppm for many of the surface waters in Washington and Oregon, to several thousand ppm in the alkaline lakes of these states. On the whole, the quality of the natural waters is good but in some areas the waters have become unsatisfactory for many purposes, including irrigation, through contamination with wastes from industrial processes, which may include drainage from irrigated lands.

Few comprehensive studies have been made to show the quality of surface and ground waters of the Northwest. The quality of some of the surface waters of Washington and Oregon is discussed in two reports [VAN WINKLE, 1914, a and b] that cover the period 1910 to 1912, but no similar recent reports are available. A few ground-water reports contain data on the quality of ground waters in small areas.

This paper will present a brief outline of the quality of water conditions as shown by the available data. The results presented may serve to show the need for further quality of water studies in this large area. Typical analyses are given in Table 1.

Analyses for ten sampling points on nine streams are given (see Table 1, 1-12). The concentrations of dissolved solids for these streams varied from 47 ppm for the Yakima at Cle Elum, Washington, and for the Santiam River at Mahoma, Oregon to 284 ppm (maximum concentration for the year) for the Yakima at Prosser, Washington. Surface waters normally show a large seasonal fluctuation. This is illustrated by the analyses given for the Yakima River at Prosser (8-10). The minimum concentration of 69 ppm occurred during a period of high runoff (17,120 cfs) in the spring. The maximum concentration of 284 ppm occurred during a period of low runoff (373 cfs) in September. The average analyses for two stations on the Yakima (7 and 9) showed an increase in concentration between Cle Elum, where the drainage area is 500 sq mi, to Prosser where the drainage area is over 5000 sq mi. This downstream increase is normal for most rivers but occasionally a river shows a lower concentration of dissolved solids at the downstream station. Such a decrease is shown by the records for Snake River (4 and 5). The average concentration for Snake River at Weiser, Idaho (drainage area 74,000 sq mi), was 220 ppm and at Burbank, Washington (drainage area 109,000 sq mi), was 131 ppm.

During storage in a large reservoir the water may become almost completely mixed. Water released from such a reservoir is essentially uniform in chemical character and concentration, and in most cases will be similar in composition to the yearly average composition of the inflow. Changes during storage may occur through precipitation of some of the dissolved solids and solution of soluble salts from the reservoir site, as has been noted for Lake Mead [HOWARD, 1946]. No data are available to indicate the changes that may take place during storage in reservoirs in the Northwest.

The quality of ground water from a given source is more uniform than the quality of surface water. Most ground waters show little variation in composition throughout the year or over a period of years. Exceptions will be found in areas where considerable quantities of ground water are pumped and for wells which draw water from more than one aquifer. Analyses of samples from 17 ground-water sources are given in the table. The concentrations of dissolved solids range from 59 ppm for the water from a shallow well (13) near Arlington, Washington, to 652 ppm for the water from a well 87 feet deep in the Harney Basin, Oregon (22). The analysis for the public water supply of Halsey, Oregon (30), shows a rather high concentration of dissolved solids (502 ppm). It is reported that saline water from the bed rock may be entering one or two wells of this supply. Analyses of water from wells of the public water supply of Canby, Oregon in the Willamette Valley (28 and 29), show a considerable difference in dissolved solids and hardness for water from two depths; the deeper water was softer but had a higher mineral content.

Table 1--Analyses of surface and ground waters from Washington, Oregon, and

No.	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
	ppm	ppm	ppm	ppm	ppm	ppm
1	17	0.04	5.2 (0.26)	1.3 (0.11)	3.7 (0.16)	1.1 (0.03)
2	17	0.06	4.4 (0.22)	1.1 (0.09)	4.1 (0.18)	1.2 (0.03)
3	24	0.07	7.2 (0.36)	1.7 (0.14)	6.1 (0.27)	1.3 (0.03)
4	26	0.04	33 (1.65)	9.6 (0.79)	22 (0.96)	3.5 (0.09)
5	19	0.05	19 (0.95)	5.6 (0.46)	14 (0.61)	
6	14	0.06	17 (0.85)	3.9 (0.32)	7.5 (0.33)	1.8 (0.05)
7	9.9	0.02	6.7 (0.33)	2.3 (0.19)	3.7 (0.16)	
8	14	0.09	10 (0.50)	3.4 (0.28)	6.1 (0.27)	
9	19	0.10	16 (0.80)	6.1 (0.50)	14 (0.61)	
10	27	0.02	37 (1.85)	14 (1.15)	35 (1.52)	
11	13	0.02	6.7 (0.33)	1.4 (0.12)	3.6 (0.16)	
12	11	0.02	11 (0.55)	3.6 (0.30)	5.3 (0.23)	
13	12	0.01	5.4 (0.27)	3.1 (0.25)	4.7 (0.20)	0.7 (0.02)
14	23	0.10	22 (1.10)	13 (1.07)	8.5 (0.37)	4.1 (0.10)
15	39	0.16[a]	37 (1.85)	22 (1.81)	27 (1.17)	4.9 (0.13)
16	23	0.01	12 (0.60)	4.4 (0.36)	9.6 (0.42)	1.2 (0.03)
17	17	0.04	6.0 (0.30)	1.3 (0.11)	5.6 (0.24)	
18	39	0.04	21 (1.05)	6.6 (0.54)	53 (2.30)	2.2 (0.06)
19	...	...	18 (0.90)	6.6 (0.54)	14 (0.61)	
20	...	...	8.5 (0.42)	7.0 (0.58)	116 (5.04)	
21	...	...	51 (2.54)	20 (1.64)	63 (2.74)	
22	51	0.01	64 (3.19)	22 (1.81)	117 (5.09)	4.0 (0.10)
23	37	0.57	51 (2.54)	27 (2.22)	39 (1.71)	
24	51	0.23	12 (0.60)	8.7 (0.72)	56 (2.45)	
25	28	b	6.8 (0.34)	2.8 (0.23)	c	
26	46	0.0	10 (0.50)	4 (0.33)	29 (1.26)	
27	44	0.12	24 (1.20)	15 (1.23)	13 (0.57)	1.3 (0.03)
28	41	0.19	24 (1.20)	11 (0.90)	7.4 (0.32)	1.8 (0.05)
29	45	0.21	11 (0.55)	5.5 (0.45)	93 (4.04)	2.9 (0.07)
30	45	0.03	74 (3.69)	23 (1.89)	55 (2.39)	1.9 (0.05)

[a]Iron in solution at time of analysis; total iron 1.1 ppm [b]3.2 ppm reported as iron and

1 Santiam River at Mehama, Ore., avg for Aug. 1 to Dec. 18, 1911, W. S. P. (Water-Supply Paper) 363, p. 94.
2 McKenzie River near Springfield, Ore., avg for Aug. 11, 1911 to Aug. 14, 1912, W. S. P. 363, p. 92.
3 Rogue River near Tolo, Ore., avg for Sept. 10, 1911 to Aug. 14, 1912, W. S. P. 363, p. 45.
4 Snake River near Weiser, Idaho, avg for Aug. 11, 1911 to Aug. 14, 1912, W. S. P. 363, p. 54.
5 Snake River near Burbank, Wash., avg for Mar. 13, 1910 to Jan. 31, 1911, W. S. P. 339, p. 75.
6 Columbia River at Cascade Locks, Ore., avg for Aug. 11, 1911 to Aug. 14, 1912, W. S. P. 339, p. 89.
7 Yakima River at Cle Elum, Wash., avg for Feb. 1, 1910 to Jan. 31, 1911, W. S. P. 339, p. 68.
8 Yakima River at Prosser, Wash., minimum concentration during Feb. 1, 1910 to Jan. 31, 1911, W. S. P. 339, p. 70.
9 Yakima River at Prosser, Wash., avg for Feb. 1, 1910 to Jan. 31, 1911, W. S. P. 339, p. 70.
10 Yakima River at Prosser, Wash., maximum concentration for Feb. 1, 1910 to Jan. 31, 1911, W. S. P. 339, p. 70.
11 Cedar River at Ravensdale, Wash., avg for Feb. 1, 1910 to Jan. 31, 1911, W. S. P. 339, p. 44
12 Spokane River at Spokane, Wash., avg for Feb. 1, 1910 to Jan. 31, 1911, W. S. P. 339, p. 56.
13 13-foot well of Wash. Coop. Chick Assoc., 3 1/2 mi SW of Arlington, Snohomish Co., Wash., Sept. 2, 1944, files of USGS.
14 26-foot well of A. B. Franzen, 3 mi NE of Marysville, Snohomish Co., Wash., Sept. 2, 1944, files of USGS.
15 150-foot well of Peter Henning, 4 mi west of Arlington, Snohomish Co., Wash., Sept. 2, 1944, files of USGS.

Idaho (values in parantheses are equivalents per million)

Bicarbonate (HCO_3)	Sulfate (S04)	Chloride (C1)	Nitrate (NO_3)	Dissolved solids	Total hardness as $CaCO_3$
ppm	ppm	ppm	ppm	ppm	ppm
23 (0.38)	4.5 (0.09)	1.0 (0.03)	0.25 (0.00)	47	18
24 (0.39)	3.8 (0.08)	1.3 (0.04)	0.2 (0.00)	50	16
38 (0.62)	4.1 (0.09)	1.4 (0.04)	0.3 (0.00)	72	25
134 (2.20)	35 (0.73)	17 (0.48)	0.6 (0.01)	220	122
83 (1.36)	21 (0.44)	8.1 (0.23)	0.5 (0.01)	131	70
69 (1.13)	12 (0.25)	3.2 (0.09)	0.5 (0.01)	97	58
32 (0.52)	6.2 (0.13)	1.6 (0.05)	0.25 (0.00)	47	26
50 (0.82)	7.9 (0.16)	1.4 (0.04)	0.0 (0.00)	69	39
80 (1.31)	21 (0.44)	5.2 (0.15)	0.34 (0.01)	123	65
174 (2.85)	62 (1.29)	16 (0.45)	0.0 (0.00)	284	150
28 (0.46)	5.7 (0.12)	1.2 (0.03)	0.2 (0.00)	49	22
48 (0.79)	9.2 (0.19)	0.6 (0.02)	0.2 (0.00)	63	42
22 (0.36)	3.2 (0.07)	6.4 (0.18)	12 (0.19)	65	26
138 (2.26)	7.4 (0.15)	7.4 (0.21)	2.7 (0.04)	151	108
233 (3.82)	1.0 (0.02)	41 (1.16)	0.1 (0.00)	271	183
69 (1.13)	6.3 (0.13)	2.0 (0.06)	0.0 (0.00)	94	48
28 (0.46)	5.9 (0.12)	1.3 (0.04)	0.1 (0.00)	55	20
199 (3.26)	1.6 (0.03)	17 (0.48)	3.4 (0.06)	246	80
100 (1.64)	14 (0.29)	5.0 (0.14)	... ...	107	72
312 (5.11)	18 (0.37)	19 (0.54)	... ...	322	50
380 (6.23)	24 (0.50)	7.0 (0.20)	... ...	352	210
151 (2.47)	175 (3.64)	138 (3.89)	0.7 (0.01)	652	250
341 (5.59)	23 (0.48)	14 (0.39)	0.2 (0.00)	360	238
195 (3.20)	4.0 (0.08)	11 (0.31)	10 (0.16)	249	61
21 (0.34)	6.3 (0.13)	3.5 (0.10)	... ...	61	28
117 (1.92)	0 (0.00)	8 (0.23)	... ...	155	41
145 (2.38)	8.2 (0.17)	12 (0.34)	3.6 (0.06)	188	122
132 (2.16)	5.0 (0.10)	4.0 (0.11)	2.4 (0.04)	163	105
258 (4.23)	4.1 (0.09)	29 (0.82)	1.0 (0.02)	326	50
211 (3.46)	2.1 (0.04)	153 (4.32)	9.0 (0.15)	502	279

aluminum oxides. [c]Less than five ppm.

16 316-foot well near Port Orchard owned by city of Bremerton, Kitsap Co., Wash., Nov. 15, 1944, files of USGS.

17 Green River, at Hot Springs, part of public supply for Tacoma, Wash., avg. for Feb. 1 to Aug. 10, 1910, W. S. P. 339, p. 46.

18 785-foot well in Tacoma, Wash., owned by city of Tacoma, part of public supply, Dec. 29, 1944, files of USGS.

19 110-foot well of Oregon Short Line R. R. Co. in Harney Basin, Ore., W. S. P. 841, p. 114 (no. 73), June 1, 1932.

20 15-foot well, owner unknown, in Harney Basin, Ore., W. S. P. 841, p. 115 (no. 124), May 9, 1932.

21 11-foot well, owner unknown, in Harney Basin, Ore., W. S. P. 841, p. 115 (no. 164), May 14, 1932.

22 87-foot well of the Harney Branch Experiment Station, Harney Basin, Ore., W. S. P. 841, p. 115 (no. 94), Sept. 1, 1931.

23 20-foot well, owner unknown, near Prineville, Ore., Nov. 22, 1946, files of USGS

24 265-foot well of Hudspeth Sawmill Co., near Prineville, Ore., Nov. 18, 1946, files of USGS.

25 Big Butte Springs, near Medford, Ore., Pub. supply of Medford., analysis by O. F. Stafford, Univ. Ore., June 20, 1925, W. S. P. 658, pp. 106-107 (no. 502).

26 Well No. 8 of the public supply of Klamath Falls, Ore., well reported to be 845 feet deep, W. S. P. 658, pp. 106-107, analysis by W. F. Langelier, Univ. Calif., Mar. c, 1930.

27 45 ±-foot well of Mountain States Power Co., Willamette Valley, Ore., public supply of Independence, Ore., W. S. P. 890, pp. 60-61 (no. 373), Oct. 13, 1928.

28 107-foot well of the municipal supply of Canby, Ore., Oct. 10, 1928, W. S. P. 890, pp. 60-61 (no. 102).

29 652-foot well of the municipal supply of Canby, Ore., Oct. 10, 1928, W. S. P. 890, pp. 60-61 (no. 103).

30 Municipal supply of Halsey Ore., dug well 28 ft deep and two wells plugged at total depth of 72 ft, Apr. 18, 1929, "Water mainly from old alluvium (some saline water from bedrock probably passes the plug)," W. S. P. 890, pp. 62-63 (no. 606).

The two analyses representing sources of the public water supply of Tacoma, Washington (17 and 18) show that the surface supply (17) has a much lower total mineral content and iron content than the ground water source.

On the basis of the available records it appears that the quality of natural waters in the Northwest is satisfactory for most uses but in some areas the available waters may be unsatisfactory for specific purposes. Changes are taking place whereby the quality of the natural waters is being impaired, and it is desirable to obtain current records in order that changes in the quality of surface and ground waters may be followed.

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U. S. Geological Survey,
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(Manuscript received July 21, 1947; presented at the North Pacific Regional Meeting, Portland, Oregon, April 22, 1947; open for formal discussion until November 1, 1948.)

DISCUSSION

David B. Charlton (Charlton Laboratories, Portland, Oregon)--There is an increasing interest being shown in the chemical characteristics of our water supplies; yet, except for a few Water-Supply Papers of the United States Geological Survey, analytical data are sparse and hard to find. For this reason the paper by Howard is indeed welcome in that it presents data, some of it previously unpublished, on both surface and ground waters, and draws attention to the fact that some of our natural waters are becoming unfit for many purposes because of contamination from industrial wastes. Fortunately, this is not yet true of our famous recreational streams, the McKenzie and the Rogue. The McKenzie water was analyzed in my laboratory recently, and it is of interest to note that our values for calcium, magnesium, sodium, potassium, silica, and bicarbonate are almost identical to those published in 1912 (W. S. P. 363). This uniformity in composition, except for variation due to floods, is certainly equal to that found in a ground water.

Howard's data included an analysis made in 1925 on water from Big Butte Springs near Medford. A sample from the same source was analyzed in my laboratory in April 1947. The values on this relatively pure water were higher but not appreciably so.

It may interest you to know that a request from the American Geographical Society was received for information on the fluorine content of Oregon waters, to be used in connection with a study of the distribution of fluorine in relation to mottled enamel and dental caries. Of the many ground- and surface-water samples analyzed for fluorine in my laboratory, a significant concentration (over one ppm) has yet to be found. However, it has been reported that one or two places in Oregon have ground waters with over one ppm fluorine.

Industrial users of water must have a complete water analysis with reference to boiler scale and corrosion problems. Most of the analytical data available were obtained years ago and usually does not give the reaction (pH) and the dissolved carbon dioxide content of the water which are most important with respect to corrosion.

I wish to make a few other observations that may be of interest to the geologists. The shallow wells and some surface waters along the length of the Oregon coast are, as a rule, lightly mineralized and fit for domestic use, except that they are acidic in character, with a reaction (pH) of about 5.0. This is very corrosive to hot-water tanks, and you will note as you drive along that the old tanks cut in two, painted in bright colors, serve as markers, legs for picnic tables, and so forth.

Many of the deeper wells in the Willamette Valley have large amounts of sodium chloride, and some give off methane gas, and the water is highly corrosive.

R. C. Newcomb (United States Geological Survey, P. O. 3418, Portland 8, Oregon)--Howard's paper on the quality of natural waters in the Pacific Northwest is timely, owing to an ever-widening local interest in the quantity and usability of water resources in the region. Lamentably, the paper also shows the poverty of data on the composition of the waters of the Northwest. Compare the half a hundred or so of published comprehensive analyses of waters from all this extensive region with the 4000-odd comprehensive analyses assembled on ground water alone by a recent investigation in the relatively small Los Angelos coastal basin in California.

Heretofore, it seems to have been sufficient to assume that the waters in the Pacific Northwest were largely quite pure, and to dismiss the systematic collection of factual data.

In the economic development of the region, water is being used in constantly greater quantities and diversity of purposes, with greater emphasis on its quality. There is widespread interest in the beneficiation of iron-bearing waters, in the securing of water of proper fluorine content, and in the softening of hard waters to economize on expensive soaps.

There is certain to be an increasing demand for data on water quality in connection with numerous relatively new industrial processes which produce synthetic materials and which have very narrow limits of tolerance for certain deleterious compounds in the water used. In couple with that pertaining to chemical character there is an increasing demand for data on temperature of water, both surface water and ground water. One new source of this demand is the interest in reverse refrigeration of ground waters as a means for space heating.

GROUND-WATER RECORDS IN RIVER-FLOW FORECASTING

Carroll F. Merriam

Abstract--Based on study of the characteristics of two elements in the recession curve, the Pennsylvania Water and Power Company has endeavored to estimate from ground-water well observation and current stream flow, the flow that can be assured one and two weeks in advance on the assumption that no subsequent rainfall might occur. Graphs indicate not only the degree of success that has been obtained but the extent to which improvement has been made by refinements not originally contemplated. The results have proved useful in guaranteeing capacity of hydro-electric plants and in the scheduling of maintenance of stream equipment.

One of the interesting practical applications of knowledge of ground water is in connection with forecasting the assured flow of the Susquehanna River. By assured flow is meant that flow which would be equaled or exceeded even though no further rainfall should occur.

Studies have shown that the total volume of ground-water storage is not sufficient to modify the hydrograph of the Susquehanna River drastically, and for that reason ground water probably plays a relatively unimportant part in influencing the peak flows at the mouth of the river in time of flood. This may not be true in other valleys, or even for parts of the Susquehanna, but ground water at present seems to have little application in forecasting the higher flows in so far as power plants located on the lower reaches are concerned.

On the other hand, at times of very low flow, the major portion of the discharge is derived from ground-water storage. It is then that a knowledge of the characteristics of the draining away of ground water permits accurate prediction, in some cases for weeks in advance, subject always to revision upward in case that rain should come.

Although quite unimportant from the point of view of total volume of flow, it is this low portion of the hydrograph which influences greatly the load carried by large power plants and in inverse measure affects the amount of steam capacity then operated on the system. Consequently, if the assured hydro-generation can be foreseen, it is thus possible to schedule the maintenance of steam equipment with confidence.

It required many years of observation before a plan could be developed for reducing all of the weekly well readings to a common index figure representative of the total amount of ground water retained in storage [MERRIAM, Trans. 1942, pt. 2, pp. 598-602]. Although perfection will never be reached in this respect, nevertheless, several years ago sufficient success was attained to permit a further study concerning the relation between this index and the ground-water discharge. It was found that the weekly index value could be considered as though it represented the elevation of the surface of an imaginary lake which had an outlet with a fixed control so that the discharge is dependent entirely upon the level of the water. Consequently, assuming no further inflow, the discharge could be predicted for weeks in advance. The fixed nature of this hydrograph was then used to estimate how long it would take for the flow to diminish to the lowest flow that could be expected at any given time of year as indicated by experience during the last half century. Even this estimate, although obviously ultra-conservative because no account was taken of the direct runoff, was useful during the War in estimating the extent to which the hydro-power could be depended upon even though rain should fail to come.

Further studies were then made concerning the maximum rate of decline of the direct runoff component of the total flow, a rough rule of thumb being that except for "freeze up" or local storm, the maximum rate of recession is approximately 20 per cent per day. This rule is useful whenever the major portion of the total is from direct runoff, but it fails when at low flows the larger portion is from ground water. By assuming that the ground-water hydrograph is a function of the ground-water index, the total flow can be divided into two parts each receding independently according to schedules which have been determined by study. Consequently, if the ground-water index is known, as well as the current total river flow, this latter may be considered as composed

of two parts, each one of which can be predicted. Forecasts are now made of each separately for seven and 14 days in advance and then they are added together. At times of severe drought it is useful to extend these forecasts to 21 days. These predictions, based upon the worst possible conditions, serve as a guide to the river forecaster so that he can proceed more intelligently in making his estimate of the probable future trend of the hydrograph after taking into account any additional knowledge he may have regarding the effect of approaching rises in the river or expected storms.

Before putting this plan into effect, it was tested by application to conditions during the previous ten years, thus making in all 520 weekly trials to determine the percentage of failures. In the seven-day predictions there were 15 failures, but all of these were associated either with "freeze ups" in winter or else with local summer storms which made the river rise suddenly and subsequently fall faster than in the case of general storms. These limitations were then recognized, to be guarded against in practice.

Forecasts were begun about two years ago, and it is now interesting to review the results during this time, as shown in Figures 1 and 2. Here the predicted values of the flow are shown

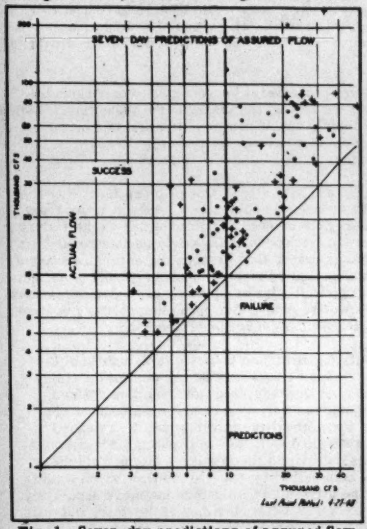

Fig. 1--Seven-day predictions of assured flow

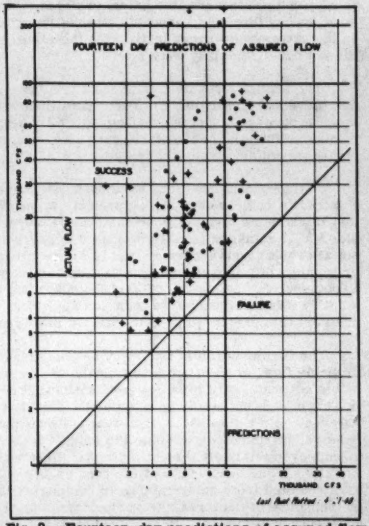

Fig. 2--Fourteen-day predictions of assured flow

plotted along the x-axis and the flow that did occur is plotted along the y-axis. A perfect prediction would fall on the line of equality, while failures would fall below this line, as in one case for the seven-day forecast. It will be noted that there were no failures in the 14-day forecasts, which might be said to be attributed to the fact that only very rarely would 14 days pass without some rain to bolster the flow.

It can also be argued that by making a sufficiently conservative guess it would be possible to avoid failures even without any knowledge such as has been gained by this study. In this case, however, the points would be grouped in random fashion, whereas it will be seen that particularly in the seven-day forecast the outline of the group conforms roughly with the line of equality. This demonstrates definitely that there is a true basis for the prediction even though the amount by which the prediction is exceeded varies in an apparently accidental fashion. In the 14-day prediction this accidental element naturally plays a more dominant part.

Although there is clear evidence of the basis for prediction shown by the diagrams, some improvement may be expected to come about as a result of increasing number of well observations. New wells are being added by the United States Geological Survey in Pennsylvania and the variations caused by individual wells and freak observations.

Beginning nearly a year ago the predictions were based on the flow as actually measured at noon by a transmitting gage just upstream from the plant. Furthermore when it was evident from up-river reports that a rise was approaching, the figure used in the computation was boosted accordingly. The effect of this change was to increase the predicted flow and consequently shift the points on these diagrams somewhat to the right and nearer the division line between success and failure. The object was of course to increase the estimate as far as could be justified, but still without the danger of the point falling on the other side of the line. That there have been no resulting failures is seen from the fact that all of the points subsequent to this change, indicated by the vertical crosses, still remain in the area of success.

The acid test came during the severe dry spell of 1947, which occurred during a critical power shortage throughout the Eastern Seaboard. It was particularly desirable to be able to predict with assurance the extent to which the hydro-power plants would be able to concentrate what energy they could generate into the hours of greatest need. The group of crossed points in the extreme low range testifies to the effectiveness of this method during a period when rain did not occur for many weeks.

The basic curves used at present are those developed several years ago, and only recently has there been opportunity to recompute them using the data as cumulated in the meantime. When as much progress as seems practical will have been made in this direction, attention will be turned to other influential parameters, such as temperature, evaporation, and season which have been neglected so far.

Two pertinent questions have been asked in regard to this study. One of these is: "Why not arbitrarily increase the 14-day prediction, possibly as much as 50 per cent, since it is apparent that to raise the dividing line would cause only a negligible number of points to fall on the failure side?" The answer is that although it appears that the prediction could safely be increased, it is not at present known whether this is because the ground-water flow exceeds the estimated amount, or whether this is caused by the fact that in two weeks some rain can almost invariably be expected. Experience during the fall of 1947 indicates that the probabilities are that the ground-water supply actually was more sustained than was supposed. However, rather than make an arbitrary upward revision it is preferred to wait until the new basic curves can be re-developed.

The second question is: "Why be concerned with the minimum possible flow instead of the probable flow, or even the flow which could be expected to be exceeded 90 per cent of the time?" If this estimate were to be the final answer, it is obvious that expected flow would be desired. However, it is but a step upon which the flow forecaster can rely as a base for subsequent allowances. By establishing first what is assured as foreseen by the flow that will be released from underground storage plus the water that is actually known to be "in transit," it is possible to improve materially the estimate that must necessarily depend upon a large number of other variables. Furthermore, as time goes on it should be possible by knowing the flow which would have resulted from prior rainfall to compare with the actual and thus determine more accurately the response of the stream to various amounts of rainfall at different times of the year, and under different conditions of soil-moisture content. Once a better knowledge of these many effects is acquired, it should then be possible to forecast more reliably the flow that should result from a given amount of rainfall.

Interest in forecasting the low flow may not be entirely confined to those power systems in which there is practical application. When there is opportunity for stream regulation for the sake of bolstering the low flow in connection with stream pollution, sanitation, navigation, provision for cooling water, and improved management of multiple purpose reservoirs advance knowledge of the conditions under which the natural flow would be abnormally low should prove of great value. However, it should be remembered that ground-water levels cannot immediately be translated into terms of useful information, like stream discharge, but a considerable period of collecting and correlating of data is necessary before any results at all are to be expected. Consequently, it is urged that wherever there is the possibility that forecasts of this nature may be desired in the future, the interested parties should at once institute a program of observation.

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TRENDS IN RUNOFF IN THE PACIFIC NORTHWEST

C. C. McDonald and W. B. Langbein

Abstract--The diminution in runoff in the Pacific Northwest, particularly the Columbia River Basin, during the past 50 years, and its hydrologic significance are discussed in this paper. An analysis of the rainfall-runoff relations for the Basin is made in order to explain the different influence of short- and long-term precipitation factors on the diminution of runoff. The indicated effects of long-term precipitation may reflect the influence of ground-water storage.

Stream-flow records of the United States Geological Survey show that the annual flow of streams in the Pacific Northwest has been progressively decreasing since about 1895. The annual flow of the Columbia River at The Dalles, Oregon, during the 28-year period (1916-1943) averaged only 81 per cent of that during the preceding 37-year period. The same general condition is found to prevail to a variable degree throughout the Basin (see Fig. 1). Over the past 60 years of active stream gaging, similar characteristics have been displayed quite generally by long records of streams in the United States and Canada [ANONYMOUS, 1945; KNAPP, 1940].

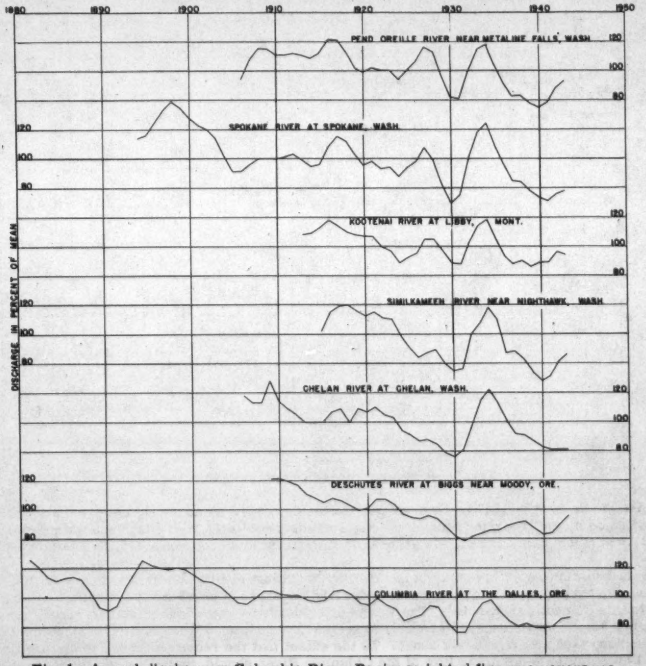

Fig. 1--Annual discharges, Columbia River Basin; weighted five-year averages

In addition to the gradual recession in stream flow there is other evidence of progressive desiccation during recent decades. Records of glacier activity indicate a decided shrinking and recession of the termini of most glaciers in the area. DYSON [1940] reports that Grinnell Glacier in Glacier National Park, Montana, was reduced in area from 0.93 sq mi in 1901-1902 to 0.38 sq mi in 1937, and Sperry Glacier was reduced from 1.31 sq mi in 1900-1902 to 0.61 sq mi in 1938. Several other glaciers in the Park show a similar tendency. The lower margin of Nisqually Glacier on Mt. Rainier, Washington, receded more than 1500 ft during the period 1910-1941 [MATTHES, 1941]. Wastage lowered the surface of the ice an average of 200 ft between the time of the first survey in 1910 and the survey in 1941. The 1946 survey indicates that the recession has continued.

Comparable climatic fluctuations have apparently occurred many times during the past several centuries. Douglass and other students of the history of the Southwest believe that climatic changes were responsible for the establishment and desertion of many of the pueblos and cliff dwellings in that area. Correlations of tree-ring widths with precipitation have provided indices of precipitation covering a period of many hundreds of years [DOUGLASS, 1919]. Figure 2 shows relative tree growth since 1800 in the Colorado River Basin, the Harney Basin, and in Eastern Oregon.

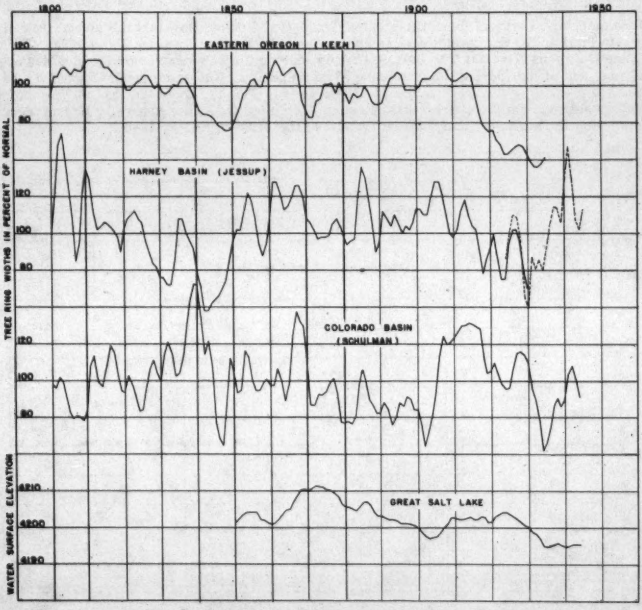

Fig. 2--Precipitation indices, smoothed curves

The historic drought of 1840 to 1850, as well as the downward trend during the past half century, are indicated by the tree-ring studies for these areas. Similarly, records of the water-surface elevation of Great Salt Lake show a general downward trend since about 1875.

Actual climatological records in the Pacific Northwest are relatively short, few records exceeding 80 years in length. These records are far too short to provide any knowledge of long-term trends or cyclic tendencies. The weight of evidence of long-term rainfall records, tree-rings, and human experience, in general, is against any continued trend toward desiccation or humidification, except in a geologic sense. To the extent that the recent decrease in stream flow is caused by climatic factors, the flow of the Columbia River should, therefore, again increase to rates comparable with those of the past.

The hydrologic sifnificance of these climatic fluctuations, however, would seem to be important in the design of a water project that may become a more or less permanent part of the economy of the country. As ultimate development of a river system is approached, the problem becomes more important. During a period of expansion and development, there is a tendency toward encroachment on the factor of safety with respect to the water supply, in order to provide a greater degree of utilization during periods of plentiful supply.

The hydraulic features of a water project involve the primary problem of determining the adequacy of the available water supply. The value of stream-flow records in this connection has long been recognized, and such records form the basis of design of most water projects. Estimates of future stream flow must of necessity be based on past records of such flow. If these records are not long enough to include critical drought periods, these estimates may be grossly in error. The relation between the climatic conditions during the period of record, and those over a longer period of time should be carefully weighed before the relatively short-term stream-flow records are used for design purposes.

In planning the scheduled comprehensive water projects in the Columbia River Basin, it seems desirable to have as complete knowledge as possible of the significance of the long downward trend observed during the past 50 years. Various contributive factors have been suggested, including a corresponding downward trend in precipitation, the wasting of the ice fields, higher mean temperatures, a progressive increase in depletion by irrigation, and the effects of other works of man. Precipitation seems unquestionably to rank as a dominant factor, and from the standpoint of the hydrologic cycle, the first factor to be appraised. Accordingly, an attempt will be made to determine whether there has been a downward trend in average precipitation over the Pacific Northwest during the first half of this century, and how the flow of the Columbia River is, in general, associated with precipitation over the Basin.

Figure 3 shows annual precipitation observed at five widely separated points in the area. A distinct downward trend is evident from about 1900 to 1935 with recovery since that time. However, in apparent contradiction to these individual long-term records it is found that state-wide averages of rainfall for the Pacific Northwest States, as published by the United States Weather Bureau since 1885, show no downward trend that compares with that in runoff. For example, the ten-year precipitation for Idaho (1934-1943) is 17.8 inches, whereas that for the ten-years of record (1886-1895) is 17.3 inches. State-wide averages are computed, it is understood, by averaging available rainfall records without regard to altitude. In the early days of the Weather Bureau, rain gages were few in number and, for the most part, were located in valley towns. The number of rain gages has steadily increased with more of them being placed at higher altitudes where rainfall is greater. For example, the average altitude of rain gages in Idaho has increased as shown in Table 1.

Table 1--Average elevations of rain gages in Idaho

Year	No. of gages	Average altitude
		ft
1901	20	3446
1920	72	3683
1945	112	3962

Consequently, there is the possibility that a downward trend in rainfall may be compensated in these state-wide averages by the increasing inclusion of rain gages at higher altitudes.

A more reliable study of trends in rainfall can be made by averaging the records of long-time stations only. This limits one to valley stations, but these might serve as an index to if not an absolute measure of the basin-wide rainfall. The records of a total of 23 rainfall stations seemed suitable for this purpose. Of these, only three stations were in operation on or before 1879, ten in 1890, 16 in 1900, and 20 in 1910. For the years with no records at one or more stations, estimates are made by comparison with records of nearby stations (including short records), making proper allowance for the characteristic or usual difference between the rainfall at the several comparative stations. This procedure reduces the computed rainfall throughout the record to a common base and avoids the difficulty occasioned by including additional stations in recent years. The method does not increase the accuracy of the computed areal rainfall in the earlier years; it merely is designed to serve to put the computed means on a common base.

Combining water-year precipitation totals, measured or estimated at the several stations, to show the effective mean over the Columbia River Basin above The Dalles is a challenging problem. As previously stated, the amounts measured at the several stations are indirectly indicative of the volume of precipitation and can be considered only as proportional measures of the volume. This assumption, although a common one, can be true only to the extent that valley and mountain precipitation varies from year to year in like degree.

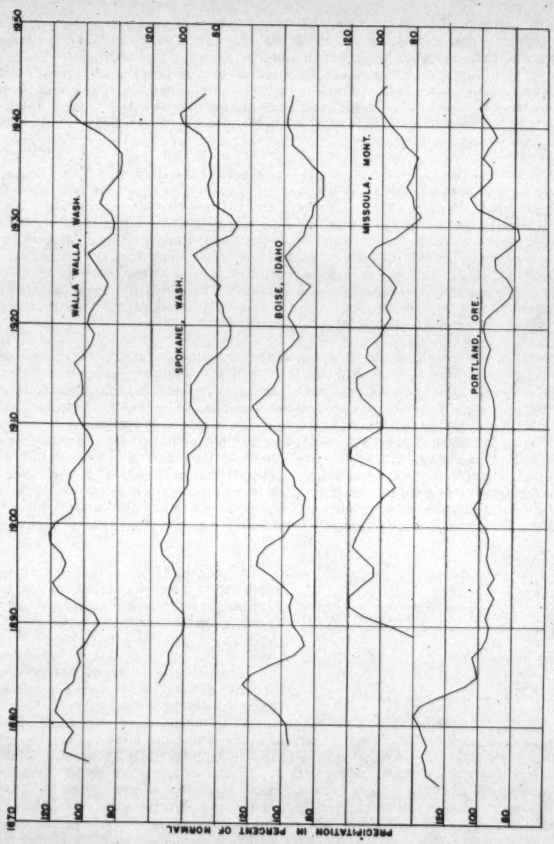

Fig. 3--Annual precipitation; weighted five-year average

As a first step, Thiessen polygons for computing weighted rainfall were constructed from the plotted network of rainfall stations. Tentative weights were assigned to the respective stations in accordance with the ratio that the area of each Thiessen polygon bears to the whole. Two methods were available for adjusting these weights. The first method was to adjust the precipitation at the stations to that estimated at the mean altitude in the respective Thiessen polygon. However, when compared with the runoff, the results seemed to give little improvement in the straight Thiessen weights. The problem was then attacked as follows.

The most general solution would be to derive by multiple correlation with the runoff, the weight assignable to each station. This procedure would involve more than 20 variables and would present a formidable task. The method was simplified by averaging the station in three groups, using the Thiessen weights; namely, upper, eastern, and western, and correlating the group averages with the runoff. The results showed that the upper and western parts of the basin should each have a weight of two, relative to one for the eastern area. This result does not mean that runoff generation is in this order, the weights merely reflect the value of the particular rainfall stations used as an index of the actual precipitation in the basin.

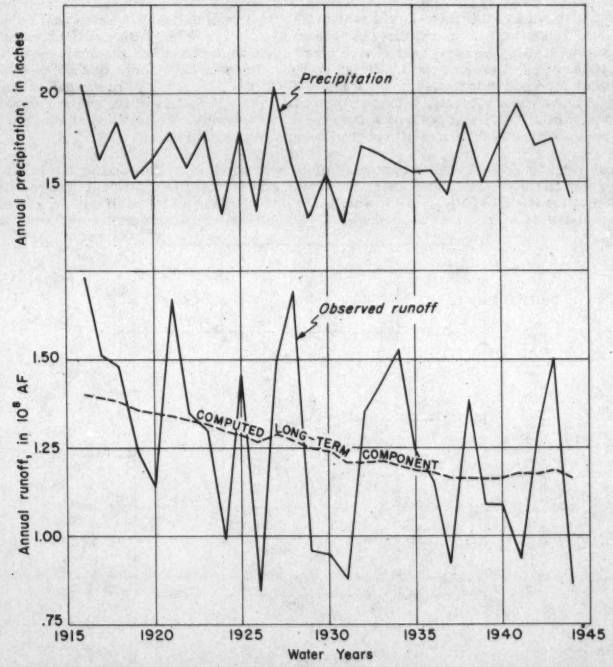

Fig. 4--Analysis of annual runoff of Columbia River at The Dalles, Oregon

Values of average annual precipitation thus derived are plotted in Figure 4. A downward trend from the beginning of the record to about 1935 is apparent, with recovery since then. Flow of the Columbia River at The Dalles has not yet exhibited such recovery. This anomaly may be attributed to a time lag of considerable magnitude between precipitation and a component of the runoff.

Such time lag may be investigated by a method which employs die-away coefficients. The primary object is to determine to what degree and in what manner the fluctuation in current and

past precipitation affect the stream flow in any given year. The evaluation is made by assuming antecendent precipitation is effective according to the simple exponential as shown by JACOB [1945] for ground-water discharge.

Thus, the effective precipitation, P_e, is given by the following formula:

$$P_e = (P_0 + KP_1 + K^2P_2 + K^3P_3 + \ldots + K^nP_n)/(1 + K + K^2 + K^3 + \ldots + K^n)$$

where P_0 is precipitation for a given year, P_1 is precipitation during the first antecedent year, P_2 is the precipitation during the second antecedent year and so on, and K is the recession ratio. The problem is to find the value of K such that P_e is most highly correlated with the observed annual runoff. The value of K ranges between zero and unity. A value of zero would be indicative of no carry-over effect so that the runoff in any year is independent of the magnitude of the precipitation in preceding years. Obviously, this condition is rarely found. Higher values of K correspond to increasing carry-over chiefly through ground-water or soil-moisture storage from preceding years.

Table 2 shows how the analysis was made. The first column lists the water years beginning with 1916. The second column indicates the observed runoff in ac ft. Although the stream-flow record begins in 1879, the early part of the record could not be used for this study because the precipitation record does not extend back far enough. The next eight columns show the effective precipitation for various indicated trial values of K. The superscripts of runoff and precipitation show the relative rank, beginning with the highest as unity. The sums of the squares of the differences in rank are shown at the foot of the respective columns. These sums of squares are used as relative measures of the correlation between precipitation and runoff.

These sums in Table 2 show a minimum for K equal about 0.2. Correlating the values of effective precipitation in this column against observed runoff indicates a straight-line relationship with the equation $R = 0.087\ P_{0.2} - 0.17$, where R is annual runoff in 10^8 ac ft and $P_{0.2}$ is effective annual precipitation in inches as listed under K - 0.2 in Table 2. If one plots cumulative observed

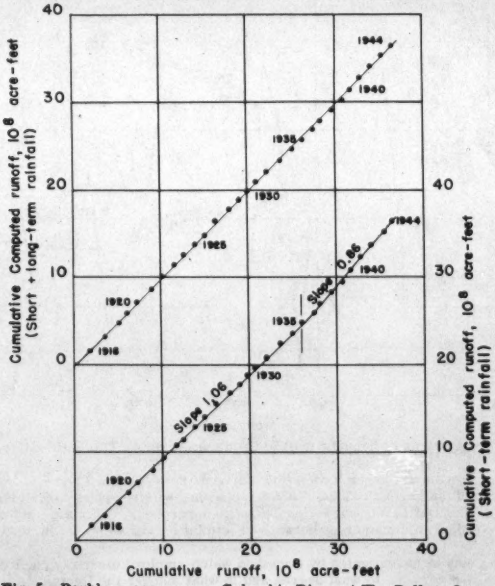

Fig. 5--Double-mass curves, Columbia River at The Dalles, Oregon

Table 2.—Analysis of carry-over—Columbia River at The Dalles, Oregon

Water year	Runoff 10^6AF	EFFECTIVE PRECIPITATION IN INCHES BASED ON TRIAL VALUES OF K INDICATED								
		0	0.1	0.2	0.3	0.5	0.7	0.9	0.95	0.98
1916	1.73	20.5	20.2	19.8	19.6	19.2	19.0	18.85	18.92	19.28
17	1.51	16.3	16.7	17.0	17.3	17.7	18.2	18.60	18.79	19.19
18	1.48	18.4	18.2	18.1	18.0	18.1	18.2	18.58	18.74	19.19
19	1.24	15.2	15.5	15.8	16.1	16.6	17.3	18.24	18.55	19.09
1920	1.14	16.3	16.2	16.2	16.2	16.4	17.0	18.02	18.39	19.04
21	1.67	17.8	17.7	17.5	17.3	17.1	17.3	18.00	18.38	18.94
22	1.33	15.8	15.9	16.2	16.2	16.4	16.8	17.78	18.20	18.76
23	1.30	17.8	17.7	17.4	17.3	17.1	17.1	17.78	18.16	18.63
24	0.99	13.2	13.6	14.1	14.5	15.2	15.9	17.32	17.87	18.45
25	1.46	17.9	17.5	17.1	16.9	16.5	16.5	17.38	17.83	18.42
26	0.86	13.3	13.7	14.1	14.4	14.9	15.6	16.97	17.55	18.21
27	1.49	20.3	19.6	19.0	18.6	17.6	17.0	17.30	17.72	18.29
28	1.68	16.0	16.4	16.6	16.8	16.8	16.7	17.17	17.60	18.24
29	0.96	13.0	13.3	13.7	14.1	14.9	15.6	16.75	17.43	18.10
1930	0.95	15.4	15.2	15.0	15.0	15.1	15.5	16.59	17.25	17.92
31	0.88	12.7	13.0	13.2	13.4	13.9	14.7	16.22	16.96	17.81
32	1.35	17.0	16.6	16.2	15.9	15.4	15.4	16.30	16.96	17.79
33	1.43	16.6	16.6	16.6	16.4	16.0	15.7	16.33	16.94	17.78
34	1.53	16.0	16.0	16.1	16.1	16.0	15.8	16.30	16.84	17.73
35	1.23	15.6	15.7	15.7	15.7	15.8	15.8	16.21	16.74	17.66
36	1.15	15.7	15.7	15.7	15.7	15.8	15.7	16.16	16.68	17.60
37	0.93	14.4	14.5	14.6	14.8	15.1	15.3	15.98	16.54	17.50
38	1.38	18.4	18.0	17.6	17.3	16.7	16.3	16.21	16.61	17.53
39	1.08	15.0	15.3	15.5	15.7	15.8	15.9	16.08	16.50	17.46
1940	1.08	17.5	17.3	17.1	16.9	16.7	16.4	16.21	16.54	17.46
41	0.94	19.4	19.2	19.0	18.7	18.0	17.3	16.52	16.67	17.43
42	1.29	17.2	17.4	17.5	17.6	17.6	17.3	16.58	16.69	17.29
43	1.50	17.5	17.5	17.5	17.6	17.5	17.3	16.67	16.73	17.43
1944	0.87	14.2	14.5	14.9	15.2	15.9	16.4	16.43	16.59	17.36
Mean	1.256			16.37					17.42	
Σd^2		1,404	1,302	(1,250)	1,338	1,332	1,664	2,260	(2,204)	2,414

runoff against cumulative computed runoff (see Fig. 5), using MERRIAM'S [1937] double-mass curve method, a marked change in slope may be noted. The change occurs about in 1935-1936. The change in slope is such as to indicate, that for a given amount of annual precipitation, a lesser amount of runoff has occurred in years following the break in the double-mass curve than formerly. The cause of such a change may be variously ascribed, but it is suggested that one explanation might be incomplete evaluation of precipitation effective in producing runoff. To explore the matter further, effective precipitation was recomputed by combining the short-term precipitation (under K = 0.2, Table 2) with a long-term effect using the values listed under K = 0.95 in Table 2. A correlation so computed yielded the following equation: $R = 0.087\ P_{0.2} + 0.09\ P_{0.95} - 1.84$ where R and $P_{0.2}$ are as before and $P_{0.95}$ is long-term effective precipitation in inches as listed under K = 0.95 in Table 2. The coefficient of multiple correlation is 0.734 with a standard error of estimate of 14 per cent of the mean. Again plotting cumulative runoff against cumulative computed of the rainfall for every year of available record back to 1853, so larger values of K can only be tested when there is longer record.

runoff using both short- and long-term precipitation, results in a double-mass curve with no apparent change in slope.

The coefficient of partial correlation of long-term rainfall on runoff is 0.40, which would be found in random data only once in 50 samples of 29 items of data. This result appears sufficiently conclusive to indicate that a significant part of the variation in the flow of Columbia River is ascribable to the effects of a long-term component of precipitation. Its influence is shown on Figure 4. The graph shows that the long-term component has been receding during the period shown. Precipitation records are not long enough to carry the graph back further. The basal component of stream flow reacts slowly to fluctuations in rainfall and serves greatly to stabilize stream flow. The effect is to sustain stream flow during receding precipitation sequences, as well as to delay the effects of a period of high rainfall. Its overall effects are considered beneficial.

The existence of carry-over of the extent indicated by the above analysis could be explained by the geology of the region. As an extreme example of the effect of the geology on the character of stream flow in the Columbia River Basin, consider the Metolius River, a tributary of the Deschutes River from the west. The drainage basin of the Metolius River lies principally in basalt. The area above the gaging station at Grandview, Oregon, is topographically determined as 325 sq mi, and most significant for the purpose of this study there is no diversion to or from, or other artificial regulation of the river above the gaging station. The stage-discharge rating of the gaging station has been comparatively stable, the only appreciable shift during the period of record since 1922, occurred during the high stage of February 1940, was less than five per cent, and was reliably defined by current-meter measurements. Records are reported good. The average annual runoff, 1922-1945, is 58.50 inches based on the area within the "topographic" divide. The runoff is uncommonly steady; the recorded extremes in flow are 5780 and 1080 cfs.

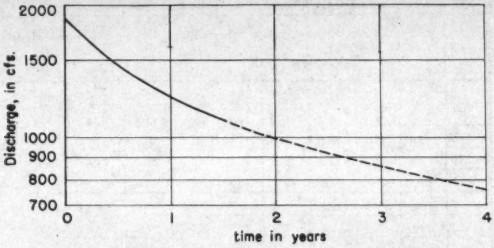

Fig. 6--Depletion graph of Metolius River at Grandview, Oregon

On Figure 6 is drawn a base-flow depletion graph of the Metolius River, derived by methods commonly used for this purpose. This graph shows that in the absence of recharge, base flow would decrease from 1800 cfs to 1100 cfs in 1.5 years; extended, the depletion graph shows that it would take about four years for the stream to recede to 750 cfs without recharge. The volume of storage necessary to maintain this flow is equal to nearly 3,000,000 ac ft, or three years normal flow of the Metolius River. Here then is ready evidence of extensive storage in this basin. The geologic features of this basin are such as to be compatible with the large storage indicated. The question is what effect does it have on the rainfall-runoff relation.

A study of the rainfall-runoff relation in the Metolius River Basin is hampered by the lack of any long-term rainfall stations in the Basin. It is not possible to estimate the volume of rainfall deposited annually in the Basin. However, nearby stations can give relative indications of the year to year anomalies in precipitation. Accordingly, the study was undertaken using United States Weather Bureau stations at Medras (1911-) and Detroit (1910-) supplemented by the rainfall-record at The Dalles (1853-) for further study of long-term trends. A study of mass curves of rainfall at these three stations [MERRIAM, 1937] revealed no inconsistencies.

The record of the Metolius River was also subjected to the same analysis as the Columbia River. The results in Table 3 indicate that the sums of the squares of the differences in rank show marked minima for K = 0.2 and 0.98. The results suggest that a value of K greater than 0.98 would give still better correlation. However, the effective precipitation using K = 0.98 includes a portion

Table 3.--Analysis of carry-over — Metolius River near Grandview, Oregon

Water year	Mean Discharge cfs	EFFECTIVE PRECIPITATION IN INCHES BASED ON TRIAL VALUES OF K INDICATED								
		0	0.1	0.2	0.3	0.5	0.7	0.9	0.95	0.98
1922	2 1,630	14 36.65	13 36.8	13 36.8	15 36.7	16 36.76	15 36.82	5 39.10	2 40.51	1 42.18
23	1 1,640	6 40.54	6 40.2	6 39.8	6 39.4	8 38.65	10 37.93	3 39.27	1 40.51	2 42.16
24	10 1,440	23 30.07	22 31.1	21 32.0	21 32.8	21 34.36	20 35.57	9 38.36	5 39.98	3 41.88
25	3 1,590	4 47.05	4 45.4	4 44.0	4 42.6	4 40.68	7 39.01	4 39.25	3 40.30	4 41.82
26	11 1,410	24 28.03	24 29.8	23 31.2	22 32.4	20 34.36	18 35.72	11 38.11	7 39.59	5 41.14
27	5 1,560	2 51.80	2 49.5	2 47.7	2 46.0	2 43.08	2 40.53	1 39.46	4 40.13	6 41.10
28	4 1,570	13 35.54	11 36.9	8 37.9	7 38.7	7 39.31	6 39.04	6 39.05	6 39.87	7 40.83
29	14 1,380	21 30.98	21 31.5	20 32.3	20 33.2	19 35.14	16 36.61	10 38.22	8 39.39	8 40.50
1930	16 1,340	20 31.69	20 31.6	22 31.8	23 32.1	23 33.40	21 35.13	15 37.53	10 38.95	9 40.03
31	22 1,230	22 30.20	23 30.3	24 30.5	24 30.7	24 31.80	24 33.65	21 36.79	12 38.51	10 39.82
32	17 1,320	16 35.14	17 35.2	18 34.6	19 34.1	22 33.77	23 34.28	23 36.66	15 38.36	11 39.71
33	12 1,400	13 36.70	15 36.5	15 36.3	18 35.9	18 35.24	22 35.01	24 36.65	18 38.26	12 39.64
34	9 1,455	10 37.30	10 37.2	11 37.1	14 36.8	17 36.27	19 35.69	22 36.70	20 38.18	15 39.40
35	8 1,466	9 38.02	8 37.9	9 37.8	10 37.6	13 37.13	17 36.37	20 36.81	22 38.15	16 39.30
36	13 1,392	7 38.48	7 38.4	7 38.3	8 38.2	11 37.80	13 37.00	18 36.97	21 38.17	18 39.29
37	15 1,346	12 36.72	14 36.6	12 37.1	12 37.1	12 37.26	14 36.92	19 36.93	24 38.11	19 39.25
38	7 1,500	3 48.41	3 47.2	3 46.1	3 45.0	3 42.84	3 40.36	12 38.06	13 38.63	14 39.50
39	18 1,317	18 33.51	18 34.8	18 36.0	13 36.9	9 38.17	8 38.30	14 37.59	16 38.36	17 39.30
1940	20 1,241	8 38.18	9 37.8	10 37.7	9 37.7	10 38.16	9 38.25	13 37.63	17 38.34	20 39.23
41	24 1,167	15 35.84	16 36.0	16 36.3	17 36.4	14 37.00	11 37.53	17 37.43	19 38.21	23 39.13
42	23 1,203	11 36.94	12 36.8	14 36.6	16 36.7	15 36.97	12 37.35	16 37.44	23 38.14	24 39.08
43	6 1,524	1 56.64	1 54.5	1 52.6	1 50.6	1 46.80	1 43.14	2 39.35	9 39.08	13 39.50
44	19 1,242	19 32.04	18 34.3	17 36.1	11 37.5	6 39.42	5 39.80	8 38.60	12 38.69	22 39.18
1945	21 1,233	5 41.23	5 40.5	5 40.2	5 40.1	5 40.31	4 40.21	7 38.84	11 38.81	21 39.19
Means	1400			37.78						40.09
Σd^2		1,466	1,234	1,122	1,252	1,518	1,816	1,108	916	614

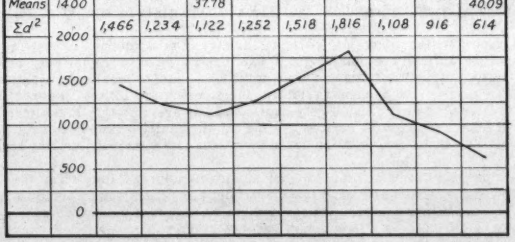

Table 3, therefore, suggests that the annual runoff of Metolius River is also affected by short-term and long-term effects. A multiple correlation between observed runoff in cfs, R, short-term rainfall, $P_{0.2}$, and long-term rainfall, $P_{0.98}$ was computed with results shown below.

$$R = 12.8\,P_{0.2} + 89\,P_{0.98} - 2650$$

where R represents the annual mean flow of Metolius River in cfs, $P_{0.2}$ the short-term precipitation for K = 0.2 as listed in Table 3, and $P_{0.98}$ the long-term precipitation for K = 0.98 as listed in

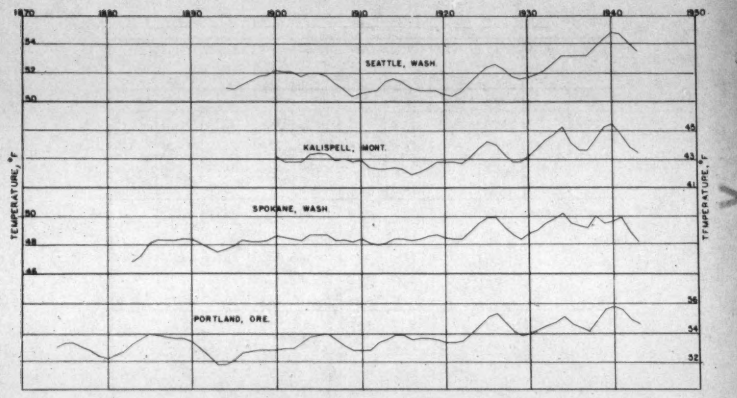

Fig. 7--Annual temperatures; weighted five-year averages

Table 3. The coefficient of multiple correlation obtained was 0.84. Of the original variance in the annual flow of the Metolius River, 37 per cent can be accounted for by the long-term component and 34 per cent by the short-term component, leaving 29 per cent as a residual unaccounted for.

It may be observed that the flow of the Metolius River is more related to long-term precipitation than to short-term. The opposite condition was noted in the flow of the Columbia River. However, it may be judged that the long-term basal component in the flow of the Columbia River is due in large part to such effects as illustrated by Metolius River. The Columbia River Basin consists of streams of wide range in character. The Metolius River probably represents one extreme. At the other extreme, there are many desert streams which flow only during intensive rainstorms. The flow of the Columbia River is a composite of all.

This study then suggests that the trends in flow in the Columbia River may be explained in part by corresponding trends in rainfall, if consideration is given to storage effects.

In general, however, the study of the effect of trends in precipitation on runoff is particularly vexing because of the difficulty in obtaining adequate estimates of precipitation, and because of the marked interrelationship between time and precipitation. In other words, to the extent that precipitation and time are not independent variables, the samples are biased. In order to be certain that the downward trend in runoff is entirely explainable by precipitation in the manner shown and is not a result of other factors also related to time, it will be necessary to defer judgment for a period of wet years until the precipitation again increases to an amount like that during the 1890's.

In the meantime, studies of other influences are highly appropriate. Thus, the increase in temperature (see Fig. 7) which has occurred throughout almost the entire period of record may be a contributing factor. Higher temperatures would tend to increase evapotranspiration losses. Again, there may be difficulty in this analysis because of bias in our samples, since rainfall and temperature are strongly interrelated. Hot and dry, cold and wet are common combinations. The increase in irrigation during the past 50 years has been a factor in the downward trend in runoff. Consumptive use by current irrigation is estimated to approximate five per cent of the mean annual flow. A more exhaustive study of the depletion by irrigation might be highly profitable.

The assistance of R. W. Carter in carrying out the computations on which portions of this paper are based is gratefully acknowledged.

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GEODETIC WORK PERFORMED IN MEXICO FROM APRIL 1946 TO MARCH 1947

Manuel Medina

(Translated by F. W. Darling and Frank L. Culley)

Triangulation

In the State of Guerrero--This triangulation, made up of nine figures and 26 stations, was completed. One of the end stations is the first-order astronomical station Inalámbrica, at which it will be possible to determine precisely the deflection of the vertical for comparison of geodetic with astronomic coordinates. A first result obtained from the preliminary computation of this triangulation is as shown in Table 1.

Table 1--Results of triangulation at Station Inalámbrica

Item	Latitude	Longitude
	° ′ ″	° ′ ″
Geodetic position	16 50 39	99 54 46
Astronomic position	16 50 21	99 55 01
Differences	+18	-15

The differences between the geodetic and astronomic positions are not surprising considering the mass of the Sierra Madre Occidental in the neighborhood of which this astronomical station is located.

On the other hand, in other Laplace positions, such as station Zacatlán, near the Sierra de Puebla, values similar to the preceding were obtained.

Triangulation on a segment of the 101st meridian--Measurement of angles was continued on this triangulation, in order to complete the observations between the 26th parallel arc and the Lerma River chain. This consists of 14 geodetic figures and 25 new stations, the mean length of the sides being about 40 km as shown in Figure 1.

Triangulation in the State of Coahuila--New triangulation was started from the side Dionisio-El Fraile of the 26th parallel arc in the State of Coahuila following the general direction of the 101st meridian northward and with the plan of continuing to the Río Grande where a new connection will be made with the triangulation of the United States Coast and Geodetic Survey.

At present reconnaissance has been made for a distance of about 260 km and is formed by five figures of which angles have been measured on the first two.

Triangulations of Sinaloa and Nayarit--The connection of the triangulations in these States has been pending for some years because of the destruction of the monuments La Punta and Yerbaniz. For this reason the triangulation of Sinaloa was computed provisionally referring it to the astronomical position El Vigía situated in the Puerto de Mazatlán. In order to refer this triangulation to the 1927 datum point and to extend it northward through the State of Sonora, it was necessary to do over part of this triangulation since it was not possible to rebuild the lost monuments as the respective references were destroyed with them. This operation, entirely completed, is shown in Figure 2.

Triangulation on the Coast of the Gulf of Mexico--Measurement of the angles of the proposed triangulation along the coast of the Gulf of Mexico, was continued, being completed between the ports of Tampico and Tuxpan. This triangulation will be used principally to locate control points which the United States Hydrographic Office will use for the hydrographic survey of the Gulf.

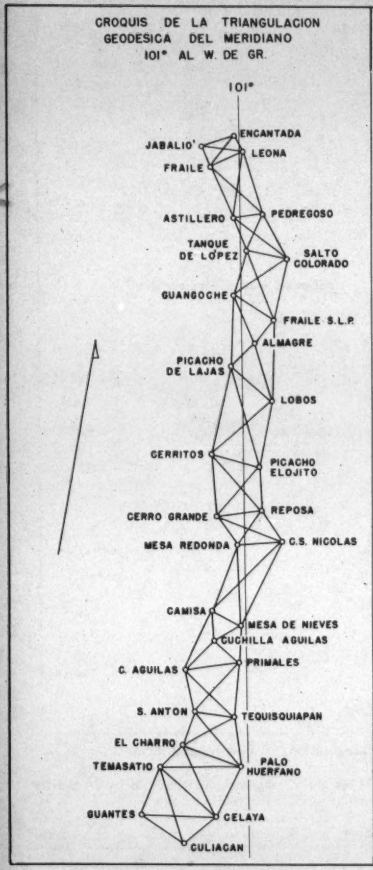

Fig. 1--Sketch of geodetic triangulation of 101° meridian west of Greenwich

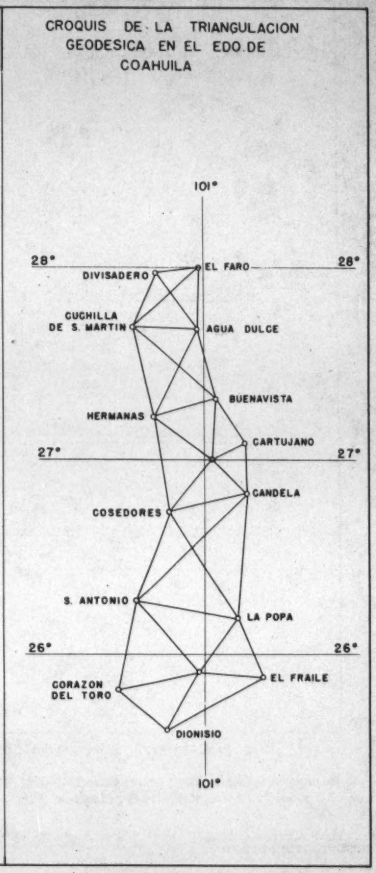

Fig. 2--Sketch of geodetic triangulation in the vicinity of Coahuila

Study and project of new triangulation--The triangulation projects in the States of Sonora and Chiapas are now being developed. The first will be a continuation of that of Sinaloa for the purpose of extending it to the boundary between Mexico and the United States. The second, or that of Chiapas, will have an international importance, since it will serve to connect the triangulation of Mexico with that of Guatemala and other Central American Republics.

Geodetic methods and standards

The geodetic standards approved at the Third Pan-American Conference on Geography and Cartography held in Caracas, Venezuela, have been put in force.

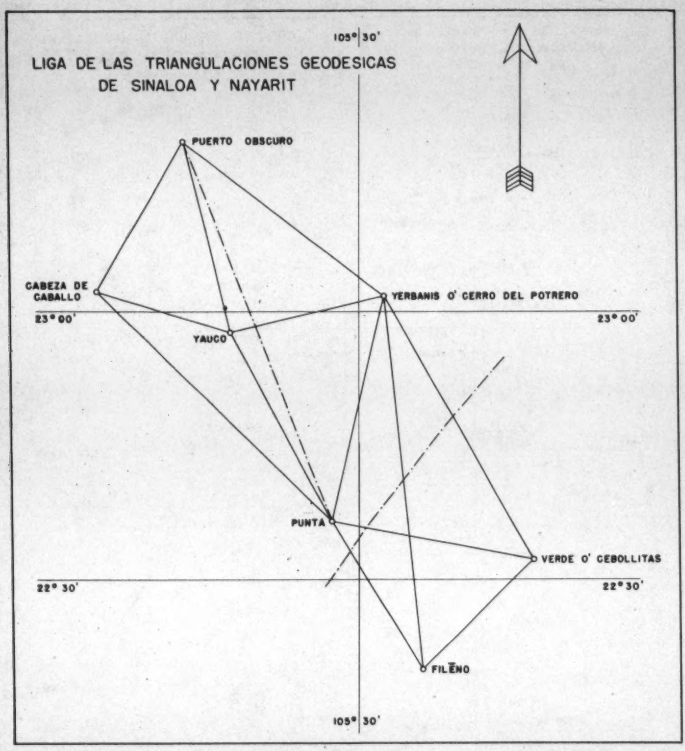

Fig. 3--Connection of the geodetic triangulations of Sinaloa and Nayarit

In regard to methods of observation, that of Bessel directions was continued to be used with use of Repsold micrometer altazimuths and Wild theodolite T-3 of the latest model.

Astronomic position--Only exploratory astronomic positions have been made for immediate cartographic purposes.

Gravity

After an interruption of gravimetric work for several years, this was resumed, making a new circuit of observations in the southeastern region of the country. In Table 2 of this report, the data obtained on the 17 recently established stations are included.

Precise levels

Included in the leveling program for the Valley of México, one level line was run out of the valley over the wheel road from México to Toluca between the level bench mark located at Tacubaya and another at the summit of the Desierto de los Leones in the Sierra Occidental. The object of this leveling was to study the conditions of stability or possible unsteadiness of the Tacubaya

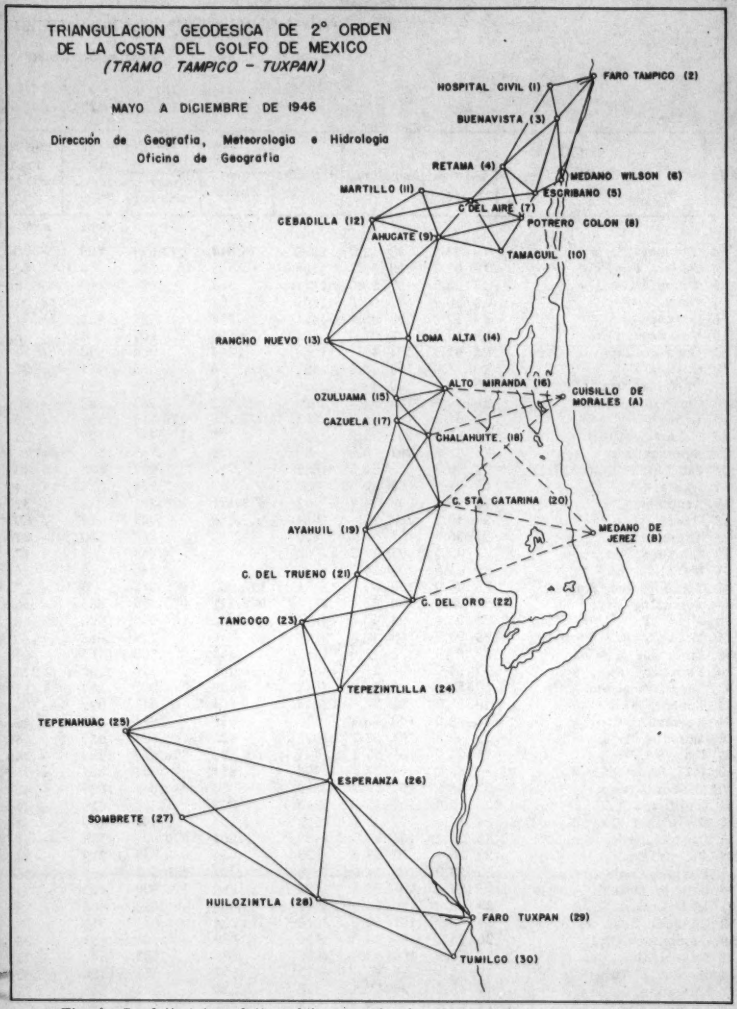

Fig. 4--Geodetic triangulation of the second order along the Coast of the Gulf of Mexico

bench mark, since there have been indications that the said bench mark suffers, although in very reduced proportion, the effects of the slow sinking of Mexico Valley.

Table 2--Results of gravimetric observations

Washington primary,

Bowie formula (1917), g = 978.039 (1 +
International (1930), g' = 978.049 (1 +

No.	Station	Latitude	Longitude	Altitude	Theoretical gravity		Free air correction	Isos. and topo. correction
					Bowie	International		
		° ′	° ′	m	gal	gal	mgal	mgal
4	Tacubaya, D. F.	19 24.3	99 11.7	2299	978.617	978.617	- 709	+ 70
5	Puebla, Pue.	19 02.7	98 12.7	2153	.587	.598	- 664	+ 69
6	Tehuacán, Pue.	18 28.5	97 23.6	1614	.557	.566	- 498	+ 55
7	Orizaba, Ver.	18 50.9	97 06.0	1241	.557	.587	- 383	+ 21
8	Jalapa, Ver.	19 32.0	96 55.0	1415	.615	.625	- 437	+ 71
9	Veracruz, Ver.	19 12.0	96 07.9	4	978.596	978.606	- 1	- 3
11	Durango, Dgo.	24 01.7	104 40.2	1866	.894	.904	- 576	+ 52
15	Colima, Col.	19 14.6	103 43.8	458	.599	.609	- 141	+ 20
17	Pachuca, Hgo.	20 07.7	98 43.9	2425	.650	.659	- 748	+ 79
18	Querétaro, Qro.	20 35.6	100 23.9	1820	.676	.687	- 562	+ 35
19	León, Gto.	21 07.5	101 40.9	1805	978.709	978.718	- 557	+ 38
20	Quanajuato, Gto.	21 01.0	101 15.3	2033	.702	.712	- 627	+ 55
21	Aguascalientes, Ags.	21 52.8	102 18.0	1869	.755	.765	- 577	+ 26
22	San Luis Potosí, S. L. P.	22 09.2	100 58.5	1865	.772	.782	- 576	+ 46
24	Iguala, Gro.	18 21.1	99 32.5	731	.550	.560	- 226	- 4
25	Acapulco, Gro.	16 50.4	99 54.7	2	978.471	978.481	- 1	+ 37
28	Quadalajara, Jal.	20 40.8	103 20.5	1584	.681	.692	- 489	+ 60
29	Tepic, Nay.	21 30.8	104 54.2	925	.732	.742	- 285	+ 57
30	San Blas, Nay.	21 32.5	105 17.3	2	.733	.744	- 1	- 12
31	Mazatlán, Sin.	23 11.3	106 25.7	5	.838	.848	- 2	- 14
32	Topolobampo, Sin.	25 36.0	109 03.0	11	979.001	979.011	- 3	+ 7
34	Tulancingo, Hgo.	20 05.0	98 22.0	2155	978.647	978.656	- 665	+ 86
35	Mina "T. H." Piso 500	20 08.4	98 40.3	2264	.650	.659	- 699	+ 18
36	Mina "T. H." Boca, Hgo.	20 08.4	98 40.3	2865	.650	.659	- 884	+141
39	Amecameca, Méx.	19 07.6	98 46.0	2468	.593	.602	- 762	+ 94
40	Tlamacas, Pue.	19 04.0	98 37.5	3885	978.589	978.599	-1199	+223
42	Cuernavaca, Mor.	18 54.9	99 14.2	1545	.581	.591	- 477	+ 19
43	Toluca, Méx.	19 17.5	99 39.6	2664	.601	.611	- 822	+105
44	Acámbaro, Gto.	20 02.0	100 43.4	1856	.644	.654	- 573	+ 45
45	Morelia, Mich.	19 42.2	101 07.2	1903	.625	.634	- 587	+ 54
46	Uruapan, Mich.	19 25.0	101 57.3	1631	978.608	978.618	- 503	+ 54
49	y 14, Zacatecas, Zac.	22 46.7	102 34.0	2596	.811	.821	- 801	+ 75
50	Fresnillo, Zac.	23 10.5	102 52.8	2226	.838	.847	- 687	+ 48
51	Cañitas, Zac.	23 30.0	102 43.0	2016	.859	.868	- 622	+ 34
52	San Juan de Guadalupe, Dgo.	24 37.0	102 45.8	1520	.934	.943	- 469	+ 1
53	Ciudad Lerdo, Dgo.	25 32.2	103 31.5	1138	978.997	979.007	- 351	- 11
54	Viesca, Coah.	25 20.7	102 48.2	1093	.984	978.993	- 337	- 24
55	Parras, Coah.	25 27.0	102 11.0	1520	.991	979.001	- 469	+ 16
56	Saltillo, Coah.	25 25.6	101 00.0	1603	.989	978.999	- 495	+ 34
57	Matehuala, S. L. P.	23 38.8	100 38.5	1576	.869	.878	- 486	+ 24
58	Charcas, S. L. P.	23 07.7	101 06.6	2006	978.834	978.844	- 619	+ 58
59	Comonfort, Gto.	20 43.2	100 45.8	1793	.684	.694	- 553	+ 38
60	Celaya, Gto.	20 31.4	100 49.0	1756	.672	.682	- 542	+ 35
64	Nevado de Toluca, Méx.	19 06.4	99 45.5	4218	.591	.601	-1302	+265
67	Cuicatlán, Oax.	17 48.2	96 57.6	640	.520	.531	- 198	- 11
68	Oaxaca, Oax.	17 03.8	96 43.4	1556	978.483	978.493	- 480	+ 65
69	Salina Cruz, Oax.	16 09.8	95 11.5	16	.438	.448	- 5	+ 5
70	Tapachula, Chis.	14 54.8	92 15.6	167	.380	.390	- 51	+ 16
73	Puerto México, Ver.	18 08.6	94 24.8	7	.539	.549	- 2	+ 6
74	Matías Romero, Oax.	16 52.9	95 02.7	204	.473	.483	- 63	- 6

in Mexico and Central America

$g = 980.117$ gal

$0.005294 \sin^2\phi - 0.000007 \sin^2 2\phi)$
$0.0052884 \sin^2\phi - 0.0000059 \sin^2 2\phi)$

Corrected gravity		Observed gravity	Probable observed error	Anomalies				Observer	Year
				American method		Mexican method			
Bowie g_c	International g'_c	g_o		Bowie $g_o - g_c$	International $g_o - g'_c$	Bowie $g_o - g_c$	International $g_o - g'_c$		
gal	gal	gal	mgal	mgal	mgal	mgal	mgal		
977.969	977.978	977.936	. .	-33	-42	. . .	. . .	A. Leyva	1912
.992	978.003	.992	0.7	0	-11	. . .	. . .	J. F. Bracho	1925
978.114	.123	978.079	0.6	-35	-44	. . .	. . .	"	"
.215	.225	.201	0.4	-14	-24	. . .	. . .	"	"
.249	.259	.243	0.2	- 6	-16	. . .	. . .	"	"
978.592	978.602	978.587	0.2	- 5	-15	. . .	. . .	"	"
.370	.380	.318	0.1	-52	-62	-53	-63	"	"
.478	.488	.426	0.4	-52	-62	. . .	. . .	"	1926
977.981	977.990	977.990	1.5	+ 9	0	. . .	. . .	"	1927
978.149	978.160	978.140	0.5	- 9	-20	. . .	. . .	"	"
978.190	978.199	978.182	0.3	- 8	-17	. . .	. . .	"	"
.130	.140	.111	3.7	-19	-29	. . .	. . .	M. Medina P.	"
.204	.214	.202	1.0	- 2	-12	. . .	. . .	"	"
.242	.252	.210	3.0	-32	-42	. . .	. . .	"	"
.320	.330	.262	2.0	-58	-68	. . .	. . .	E. Ruiz	"
978.507	978.517	978.527	1.0	+20	+10	. . .	. . .	"	"
.252	.263	.203	1.0	-49	-60	. . .	. . .	"	1928
.504	.514	.469	0.6	-35	-45	. . .	. . .	"	"
.720	.731	.710	0.5	-10	-21	. . .	. . .	"	"
.822	.832	.850	0.4	+28	+18	. . .	. . .	"	"
979.005	979.015	978.999	1.0	- 6	-16	. . .	. . .	"	"
978.068	978.077	.034	0.4	-34	-43	. . .	. . .	"	"
977.969	977.978	977.984	1.0	+15	+ 6	. . .	. . .	"	"
.907	.916	.906	1.0	- 1	-10	. . .	. . .	"	"
.925	.934	.900	0.8	-25	-34	. . .	. . .	"	"
977.613	977.623	977.577	5.0	-36	-46	. . .	. . .	"	"
978.123	978.133	978.106	1.0	-17	-27	. . .	. . .	"	"
977.884	977.894	977.852	1.0	-32	-42	. . .	. . .	"	"
978.116	978.126	978.081	0.8	-35	-45	. . .	. . .	"	"
.092	.101	.066	0.3	-26	-35	. . .	. . .	"	"
978.159	978.169	978.133	0.8	-26	-36	. . .	. . .	"	"
.085	.095	.084	0.5	- 1	-11	. . .	. . .	"	1930
.199	.208	.198	0.8	- 1	-10	. . .	. . .	"	"
.271	.280	.265	0.4	- 6	-15	. . .	. . .	"	"
.466	.475	.472	0.5	+ 6	- 3	. . .	. . .	"	"
978.635	978.645	978.640	0.9	+ 5	- 5	. . .	. . .	"	"
.623	.632	.619	0.8	- 4	-13	. . .	. . .	"	"
.538	.548	.552	0.7	+14	+ 4	. . .	. . .	"	"
.528	.538	.527	0.5	- 1	-11	. . .	. . .	"	"
.407	.416	.382	0.9	-25	-34	. . .	. . .	"	"
978.273	978.283	978.234	0.4	-39	-49	. . .	. . .	"	"
.169	.179	.150	0.8	-19	-29	. . .	. . .	"	"
.165	.175	.143	1.4	-22	-32	. . .	. . .	"	"
977.554	977.564	977.516	0.4	-38	-48	-37	-47	"	1932
978.311	978.322	978.262	0.6	-49	-60	-51	-62	"	1933
978.068	978.078	978.028	0.7	-40	-50	-39	-49	"	"
.438	.448	.394	0.7	-44	-54	-43	-53	"	"
.345	.355	.323	2.1	-22	-32	-23	-33	"	"
.543	.553	.525	1.0	-18	-28	-17	-27	E. Paquentín	1935
.404	.414	.414	0.7	+10	0	+11	+ 1	"	"

Table 2--Results of gravimetric observations

No.	Station	Latitude		Longitude		Altitude	Theoretical gravity		Free air correction	Isos. and topo. correction
							Bowie	International		
		°	′	°	′	m	gal	gal	mgal	mgal
75	Tonalá, Chis.	16	05.2	93	45.5	52	978.434	978.444	- 16	- 4
76	Tuxtla Gutiérrez, Chis.	16	45.5	93	07.0	508	.467	.477	-157	+ 30
78	Guatemala, Guat.	14	34.5	90	32.0	1489	.365	.375	-460	+100
79	San Salvador, El Salvador	13	43.7	89	09.5	674	.330	.340	-208	+ 60
80	La Unión, El Salvador	13	20.0	87	51.0	10	.313	.323	- 3	+ 6
81	Tegucigalpa, Honduras	14	06.0	87	13.5	975	978.345	978.354	-301	+ 62
82	Managua, Nicaragua	12	09.5	86	16.0	47	.268	.278	- 15	+ 18
85	Rio Verde, S. L. P.	21	55.9	99	59.6	991	.758	.768	-306	+ 14
86	Ciudad Valles, S. L. P.	21	59.1	99	01.0	84	.761	.771	- 26	+ 36
87	Tampico, Tams.	22	13.0	97	51.3	16	.776	.786	- 5	+ 10
88	Ciudad Victoria, Tams.	23	44.1	99	07.8	321	978.875	978.884	- 99	- 9
89	Monterrey, N. L.	25	40.2	100	18.4	538	979.006	979.016	-166	- 43
92	Ciudad Juárez, Chih.	31	44.3	106	29.2	1144	.466	.476	-353	+ 18
83	Chihuahua, Chih.	28	38.2	106	04.7	1430	.224	.233	-441	+ 39
94	Parral, Chih.	26	56.1	105	40.0	1740	.097	.107	-537	+ 48
97	Puerto Limón, Costa Rica	10	00.0	83	01.0	3	978.194	978.204	- 1	+ 17
98	San José, Costa Rica	9	56.0	84	04.0	1175	.192	.202	-363	+107
99	Punta Arenas, Costa Rica	9	58.0	84	49.0	4	.193	.203	- 1	+ 15
102	Tierra Blanca, Ver.	18	27.3	96	20.0	60	.555	.565	- 19	- 37
103	Rodríguez Clara, Ver.	18	00.0	95	23.8	136	.532	.541	- 42	+ 1
104	Villahermosa, Tab.	17	59.2	92	55.0	20	978.531	978.540	- 6	+ 12
105	Salto de Agua, Chis.	17	36.0	92	25.0	141	.510	.520	- 44	+ 4
106	Balancán, Tab.	17	48.1	91	31.8	18	.521	.530	- 6	+ 12
107	Xicalango, Camp.	18	37.9	91	53.5	2	.564	.575	- 1	+ 26
108	Escárcega, Camp.	18	36.8	90	43.5	107	.563	.574	- 33	+ 27
109	Central Villahermosa, Camp.	17	55.1	89	47.8	229	978.527	978.537	- 71	+ 35
110	Central Nohsayab, Camp.	18	44.0	89	14.0	145	.570	.580	- 45	+ 34
111	Chetumal, Q. Roo	18	29.6	88	18.0	4	.558	.567	- 1	+ 45
112	Carrillo Puerto, Q. Roo	19	34.8	88	02.5	20	.618	.628	- 6	+ 32
113	Puerto Morelos, Q. Roo	20	48.0	86	56.5	2	.689	.699	- 1	+ 53
114	El Cuyo, Yuc.	21	31.2	87	40.8	3	978.732	978.742	- 1	+ 32
115	Valladolid, Yuc.	20	41.4	88	12.2	24	.682	.692	- 7	+ 31
116	Peto, Yuc.	20	07.6	88	55.5	26	.649	.659	- 8	+ 25
117	Mérida, Yuc.	20	58.1	89	37.2	9	.699	.709	- 3	+ 25
118	Campeche, Camp.	19	50.8	90	32.2	8	.633	.643	- 2	+ 22

Cartography and photogrammetry

During the last months of the past year, publication of the following maps was completed: State of Jalisco, at the scale of 1:500,000 with 200-m contour intervals; State of Puebla, at the scale of 1:200,000 with 200-m contour intervals; State of Tabasco, at the scale of 1:200,000 with 100-m contour intervals; State of Tamaulipas, on the scale of 1:400,000 with 200-m contour intervals; State of Zacatecas, on the scale of 1:500,000 with 100-m contour intervals; and Lower California on the scale of 1:650,000, partly contoured.

The contouring of these maps, except that of Jalisco which was taken originally from trimetrogon photographs, was the result of interpolation of contours which appear on the maps of Mexico on the scale of 1:500,000 published by the Air Force of the United States. This contouring is provisional while it could be improved with data which vertical photogrammetry would provide.

in Mexico and Central America (concluded)

Corrected gravity		Observed gravity	Probable observed error	Anomalies				Observer	Year
				American method		Mexican method			
Bowie g_c	International g'_c	g_o		Bowie g_o-g_c	International $g_o-g'_c$	Bowie g_o-g_c	International $g_o-g'_c$		
gal	gal	gal	mgal	mgal	mgal	mgal	mgal		
978.414	978.424	978.368	1.6	-46	-56	-43	-53	E. Paquentín	1935
.340	.350	.288	0.5	-52	-62	-52	-62	....	"
978.005	.015	977.968	2.9	-37	-47	-35	-45	E. Ruiz	1936
.182	.192	978.180	0.9	- 2	-12	- 2	-12	"	"
.316	.326	.325	1.4	+ 9	- 1	+ 7	- 3	"	"
978.106	978.115	978.097	2.0	- 9	-18	-12	-21	"	"
.271	.281	.273	0.9	+ 2	- 8	+ 5	- 5	"	"
.466	.476	.444	0.6	-22	-32	-23	-33	"	1937
.771	.781	.720	1.2	-51	-61	-51	-61	"	"
.781	.791	.796	1.5	+15	+ 5	+14	+ 4	"	"
978.767	978.776	978.759	0.5	- 8	-17	- 7	-16	"	37-38
.797	.807	.802	0.8	+ 5	- 5	+ 8	- 2	"	1938
979.131	979.141	979.104	1.5	-27	-37	-26	-36	"	1940
978.822	978.831	978.764	1.6	-58	-67	-56	-65	"	"
.608	.618	.577	0.6	-31	-41	-32	-42	"	"
978.210	978.220	978.219	0.3	+ 9	- 1	+ 9	- 1	"	"
977.936	977.946	977.928	2.3	- 8	-18	- 8	-18	"	"
978.207	978.217	978.225	1.9	+18	+ 8	+18	+ 8	"	"
.499	.509	.492	1.3	...	...	- 7	-17	"	45-46
.491	.500	.451	0.6	...	...	-40	-49	"	1946
978.537	978.546	978.516	1.2	...	...	-21	-30	"	"
.470	.480	.459	0.4	...	...	-11	-21	"	"
.527	.536	.509	1.3	...	...	-18	-27	"	"
.589	.600	.541	1.5	...	...	-48	-59	"	"
.557	.568	.541	1.1	...	...	-16	-27	"	"
978.491	978.501	978.472	0.9	.	...	-19	-29	"	"
.559	.569	.540	0.5	...	...	-19	-29	"	"
.602	.611	.595	0.8	...	...	- 7	-16	"	"
.644	.654	.658	1.4	...	...	+14	+ 4	"	"
.741	.751	.764	0.6	...	...	+23	+13	"	"
978.763	978.773	978.754	0.6	...	...	- 9	-19	"	"
.706	.716	.694	0.8	...	...	-12	-22	"	"
.666	.676	.660	1.0	...	...	- 6	-16	"	"
.721	.731	.694	0.4	...	...	-27	-37	"	"
.653	.663	.645	0.8	...	...	- 8	-18	"	"

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EARTHQUAKE STUDY IN SOUTHERN CALIFORNIA, 1947

B. Gutenberg and C. F. Richter

(Contribution No. 405, Balch Graduate School of the Geological Sciences)

This continues the previous report by GUTENBERG and RICHTER [1947]. Papers published during the year are also listed under FU [1947]; RICHTER [1947]; and WOOD [1947].

The book presenting revised study of the seismicity of the Earth will be published by the Princeton University Press. Until publication, the manuscript will be continuously revised to keep it up to date.

Reports on the following research were prepared for the meetings of the Seismological and Geological Societies of America at Pasadena in April 1948.

Gutenberg has investigated seismograms at epicentral distances from four degrees to 26°, constructed revised travel times for P and S, and determined the amplitudes of both phases as functions of distance. All observations are explained on the assumption that the velocities of both P and S decrease by roughly one per cent in the depth range below the Mohorovičić discontinuity, reach minima at about 80-100 km below the surface, and increase again at about 150 km below which Poisson's ratio remains near 0.30, appreciably higher than its values (near 0.25) in the upper layers.

J. M. Nordquist and L. P. Geldart have investigated coincidences in calendar date between earthquakes in the same area in different years. Such coincidences, at first sight surprisingly numerous, agree closely with the theoretical expectancy on the hypothesis of purely random occurrence.

Hugo Benioff is engaged on investigation of the release of energy in sequences of earthquakes. This includes aftershocks and also the general seismicity of limited regions, and applies to deep as well as to shallow shocks. Preliminary results indicate that each sequence forms an elastic, plastic, or combination elastic-plastic creep series.

C. H. Dix has consulted with those constructing the new electronic digital computer at Princeton, and is considering applications of this and other machines to seismology and geophysics.

The Manix earthquake [RICHTER, 1947] in the central Mojave Desert, developed fault trace phenomena on a very small scale (displacements of a few inches traceable for two to three miles) indicating left-hand strike slip on the roughly east-west Manix fault. This feature has been investigated with reference to the regional geology by J. P. Buwalda and C. F. Richter.

The instrumental records of aftershocks of the Manix earthquake have been studied by Richter and Nordquist. The data clearly indicate a line of epicenters trending slightly south of east from that of the main shock; this line is transverse to the Manix fault.

Response of the strain seismometers has been improved by a new transducer, and a second component at right angles to the first strain instrument has been installed.

Physical constants of all the Pasadena instruments have been checked, and some adjustments made. Figure 1 illustrates the response curves (to continuous sinusoidal waves) for seismometers now in routine service.

Construction has been commenced on a tiltmeter unit.

Routine bulletins for teleseisms and local shocks have been issued through June and December 1947, respectively.

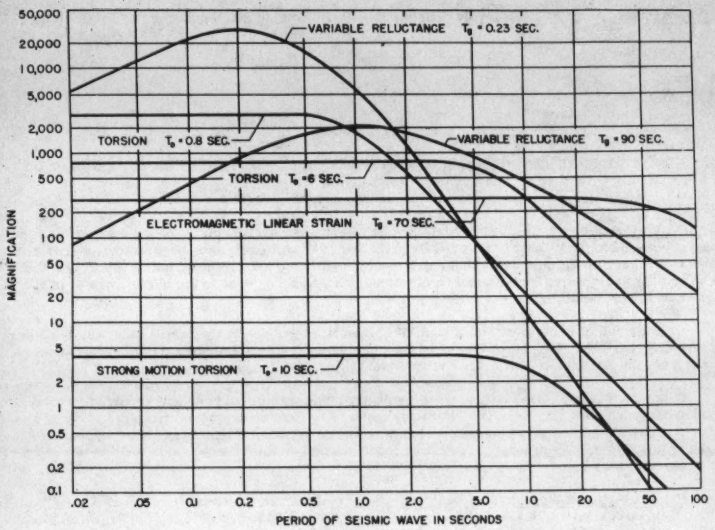

Fig. 1--Standard response curves for instruments in routine service at Pasadena

The most important shocks in the southern California area during 1947 were the Manix earthquake of April 10 (magnitude 6 1/2 or over) and a shock near Morongo Valley on July 24 (magnitude 5.5).

No great earthquake (magnitude 7 3/4 or over) occurred anywhere in the World during 1947. The Philippine earthquake of January 24, 1948, was of magnitude 8 at least.

References

FU, C. Y., On seismic rays and waves (Pt. 1), Bull. Seis. Soc. Amer., v. 37, pp. 331-346, 1947.

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RICHTER, C. F., The Manix (California) earthquake of April 10, 1947, Bull. Seism. Soc. Amer., v. 37, pp. 171-179, 1947.

WOOD, HARRY O., Earthquakes in southern California with geological relations (Pts. 1 and 2), Bull. Seis. Soc. Amer., v. 37, pp. 107-157, 217-258 + 4 maps, 1947.

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DISCUSSION OF

"SOME RECENT EVAPORATION INVESTIGATIONS" by ARTHUR A. YOUNG

[Trans., v. 28, pp. 279-284, 1947]

N. W. Cummings (768 Twenty-sixth St., San Bernadino, California)--Young's paper, and the two processed reports which preceded it, [YOUNG, 1942 and 1945] have been examined with respect to the following question: Can any pan add anything to knowledge of lake evaporation that can readily and cheaply be obtained by other means, and if so, what is the best design of pan, and how can it best be used?

The method of using the combination of an insulated pan and temperature data, has been described by CUMMINGS [1946]. But when the supplementary data are not available and cannot be procured, the possible use of a pan alone, deserves careful consideration.

Although Young's observations were evidently made with great care and reported in complete and orderly manner, the entire investigation appears to have been planned from the point of view of a pan-to-lake coefficient, with special emphasis on the Weather Bureau pan. The value of the study must, therefore, in large measure at least, depend on the inherent possibilities of such a coefficient.

Regional significance of pan-to-lake coefficient--Although the average of Young's coefficients for the three full years at Lake Elsinore is 0.78 [YOUNG, 1942, Tables 5, 6, and 7], he mentions 0.77 as the figure for the Weather Bureau pan in the Southwest. His reason for naming 0.77 is not clear. At Bear Lake in Utah and Idaho, the coefficient for July, August, and September 1937, turned out to be 0.86. If we regard Lake Elsinore as an instrument for estimating the loss at Bear Lake, the coefficient would have to be (0.191 inches per day × 92 days) = (17.6/22) = 0.80.

It is interesting to examine these figures from the standpoint of precision. The data for the Weather Bureau pan and Lake Elsinore for July, August, and September for the years 1938 through 1941, and the figures for the same months at Fort Collins, Colorado [ROHWER, 1931] for 1927 and 1928 are shown in Table 1.

Table 1--Evaporation data for Elsinore and Fort Collins

Year	Elsinore		Year	Fort Collins	
	Ratio	Departure from average		Ratio	Departure from average
1938	0.73	0.04	1927	0.74	0.02
39	0.78	0.01	28	0.70	0.02
40	0.74	0.03	...	...	...
41	0.84	0.07	...	...	...
Aver.	0.77	0.0375	Aver.	0.72	0.02

Thus, for the summer months at Elsinore, the average coefficient is 0.77, substantially Young's average for the year, whereas the average departure from the average, when all determinations were made at the same locality, is 0.0375, which is about five per cent of the coefficient. At Fort Collins the corresponding figures are 0.72, 0.02, and three per cent.

At Bear Lake the problem was not the exceptionally easy one presented by Elsinore and Fort Collins, since the lake evaporation could not be measured directly, but had to be estimated from energy considerations [CUMMINGS, 1946]. Therefore, it is to be expected that the error may, at the present stage of development of the energy idea, be somewhat larger than a mere departure obtained by applying an average coefficient to the identical data from which the average coefficient was derived. The greatest uncertainty occurs in averaging R for the lake, over a daily cycle. The

outer limit for the error in this determination appears to be 0.14, which corresponds to about 12 per cent of the evaporation. For comparison with the foregoing average departures, we may arbitrarily divide this by 2 and add four per cent for other errors, making the lake estimate subject to an over-all error of ten per cent.

We must conclude then that the difference between the Elsinore and Bear Lake determination of the Weather Bureau pan coefficient can be explained on the basis of a combination of the experimental errors at the two places. It appears to be straining things, however, to account for the Fort Collins comparison on this basis. We must accordingly draw the startling inference that the coefficient for the Southwest applies in Intermountain country better than does the coefficient for the Intermountain Region.

There seems to be no escape from the conclusion that the regional significance which has been attached to pan-to-lake coefficients, needs clarification. A lake-to-lake coefficient as high as 0.80, when viewed in the light of the large spread in pan-to-lake coefficients, indicates that local variations within a region are comparable in order of magnitude to the difference between regions. This suggestion is supported by the fact that at Lake Elsinore the average departure from the summer average pan-to-lake coefficient was half as large as the departure of either Bear Lake or Elsinore from the average of the two lakes.

Now if a pan-to-lake coefficient can, under the very most favorable circumstances, do no better than cut the error in half, should we not raise a serious question as to the usefulness of such a coefficient? In ordinary operations, a Weather Bureau pan coefficient will be subject to many errors that were absent from Young's observations. The water level will get too low or will sometimes get too high so that spilling will occur in high winds. Inadequate corrections will be made for rain, animals will occasionally fall into the pan or drink water from it, birds are sometimes a source of trouble, and the pan may be shaded by fence posts or other obstacles. Yet we have still not taken account of the possible variation of the pan-to-lake coefficient as applied to different lakes.

Similarities at different localities--With all these extraneous errors added to the intrinsic error of the pan-to-lake coefficient itself, there seems to be little hope that any pan is worth the installation cost unless it is to be used in a scientific manner. The more practical thing is to assume temporarily, as a broad working principle, that all lakes evaporate alike, and then formulate cooperative plans for the intensive study of a reasonable number of actual lakes. The procedure has been explained by CUMMINGS [1946].

This plan is supported by an examination of Horton's data for the Bureau of Plant Industry (BPI) and Weather Bureau pans [HORTON, 1934, pp. 361-363]. If we place the confidence that Young suggests, in the 12-foot pan, we must also place great confidence in the BPI pan, for his table shows a negligible departure from the average coefficient of 0.94.

The April to September average for the 27 BPI pans which Horton gives, and which are fairly well scattered over the United States, is 41 inches, with an average departure of 6.3 inches or 15 per cent. This figure compares favorably with both the Elsinore and Bear Lake results which are, Elsinore 39 inches for the months Horton used, and Bear Lake 17.6 inches for July, August, and September.

We may note further that the range of variation of computed insolation as obtained from the table given by BRUNT [1941, p. 112] for the months Horton used, between latitude 20° and 45° is (186-176) arbitrary units, or about 5.5 per cent, suggesting a small range of variation of summer lake evaporation with latitude.

Also the average of 65 Weather Bureau pans which Horton gives is 44.4 inches for May through October, which can presumably be reduced to the same interval as that for the BPI pans by dividing by 0.978. The figure so obtained is 45.3 inches. The average departure is 11 inches or about 25 per cent, which consists of three types of error: (a) The erratic departure of an individual pan from the general trend of its locality; (b) the variation of radiation and atmospheric conditions at different places; and (c) lack of proper cure of the pans.

Merely for the sake of obtaining suggestive comparisons, we may assume the total error to be the arithmetic sum of the separate ones, and may assign the five per cent obtained at Elsinore as the magnitude of error (a). For error (b) we can do no better than use the ten per cent departure of Elsinore and Bear Lake from their average. This leaves ten per cent for error (c) which, upon inspection of the data does not seem excessive. How, for example, can a maximum six months' evaporation be as low as 16.8 or as high as 72.8 inches?

The ratio of the averages for the two pans is (41/45) = 0.91, which is about nine per cent greater than Young obtained at Fullerton. This much difference can be accounted for without the assumption of any variation of evaporation with geographical position, although of course we do not need to assume the total absence of such variation. Moreover, since there is no reason to assume greater variation in radiation and atmospheric conditions at the locations of the Weather Bureau than the BPI pans, we must assign the greater scatter of the former to causes (a) and (c), both of which can reasonably be assumed greater for the Weather Bureau pan.

There are three reasons for this: (a) The greater diameter and burial in the soil are likely to make the BPI pan act as if it were thermally insulated and thus prevent erratic heat leakage through the walls. (b) The true average temperature (not the mean of the maximum and minimum) may be higher for the larger pan, especially when heat leakage is relatively small. With the understanding that all energy components are reduced to a basis of unit area of open water surface, we may say that the algebraic sum of all the incoming or negative ones other than radiation, must be greater for the smaller pan, on account of the greater depth of the water lost. If heat leakage is below a certain magnitude, this greater influx of energy for the smaller pan, necessarily means a lower surface temperature for that pan. If heat leakage is above the critical magnitude, a lower temperature would still induce a greater influx of heat, but the converse is not necessarily true. That is, if the temperatures are equal, or slightly greater for the smaller pan, while convection and back radiation differences are negligible, the smaller pan might get a greater total flux of energy per unit area of open-water surface. In this case, however, the relative leakages as discussed under (a) would be highly important. Also the greater depth of the BPI pan tends to shift the evaporation toward that part of the daily cycle during which the water is warmer than the air. This condition as well as the higher temperature when it exists, tends to cause the energy ratio or so-called Bowen ratio to be on the average more strongly positive or less strongly negative for the BPI pan, which in turn causes it to be less sensitive to variations in water-surface temperature. In so far as water-surface temperature is itself influenced by atmospheric conditions, the higher energy ratio tends toward general stability of the larger pan. (c) The more expensive BPI pan is less likely to be installed without adequate provision for its proper care.

The energy ratio has never been found to average as much as 30 per cent for a 24-hour cycle, and its variation with geographical position is probably quite negligible, especially for a lake or large pan. Since the variation of the radiation that would occur with clear skies, is known to be small throughout the summer season for such an area as the continental United States, the only way in which large variations of lake evaporation with geographical position could occur, would be through large variation in cloudiness. Such large variations do not occur where lake evaporation is of greatest importance, as can readily be ascertained by an inspection of the pyrheliometer data published in the Monthly Weather Review.

This means the practical problem of determining lake evaporation, as it relates to water-supply investigations, reduces to the measurements of small departures from the general average of about 40 inches for the highest six months. All instruments for the purpose, should be designed and used with this thought in mind. It is far better to choose a few stations at which measurements can be made which are capable of clear, reliable interpretation, than to make erratic observations at a large number of places. Naturally, distribution throughout the season should be estimated whenever necessary, but here again, the energy idea seems the most useful now available.

Rim effect and screened pan--It seems advisable to deal simultaneously with the so-called rim effect, and with Young's suggestion of a screened pan.

Of course the metal which projects above the water collects a certain amount of solar and sky radiation, and transmits a small fraction to the water, although it is difficult to see how capillarity has anything perceptible to do with it.

Undoubtedly the main reason for the larger relative evaporation from small pans is the turbulence at the rim as shown by Albertson's photographs [ALBERTSON, 1946, p. 60]. This turbulence cools the water, causing the energy ratio to lean more strongly toward the negative for the pan than for the lake, and the smaller the pan, the greater the difference, although other aspects of turbulence may cause the energy ratio to be about the same for a 12-foot pan as for the lake.

The proper pan design therefore does not involve screening but tends somewhat in the opposite direction. From the standpoint of the operation of a pan over a 24-hour cycle, the most important energy components are (a) radiation, (b) evaporation, (c) convection, and (d) leakage through the walls.

Screening is sure to decrease (a), (b), and (c), while its effect on (d) is unpredictable and therefore bad. The chances are better than even that it will make (d) large in comparison to the others, which is exactly the opposite of what we want. Correct design aims to keep (c) and (d) as small numerically as possible in relation to (a) and (b) or to make (c) somewhat positive. It is thus seen that by producing such an effect on (c), screening does one desirable thing, and an examination of Young's data provides some reason for supposing that the component of convection from air to water may be decreased more, relatively, than radiation and evaporation.

Suggested design for pan--This thought leads to an artifice that would eliminate the rim effect and at the same time exploit whatever advantage may be gained by screening. It consists of a flat ring resting on the rim and projecting two or three inches inward and one or two inches outward. Its thermal coupling with the rim should not be tight, and the edge of the opening sould be adapted to discharge all rain outside of the pan.

Wave action would thus be prevented from causing any spilling, the rim would be completely shaded, the percentage of shaded water surface would be definite, and turbulence at the initial contact of the moving air with the water surface would be greatly diminished. With such a design, radiation on the water surface would be diminished by, let us say, one third, and evaporation by perhaps ten per cent more on account of a shift of the energy ratio toward the positive. Shading of the rim tends to prevent heat leakage into the pan, but on account of the obstructed opening, outward leakage might be increased if adequate thermal insulation is not provided. But that should be done in any case. It might be done by cylindrical baffles having diameters slightly less than of the pan so as to cause the outer shell of water to remain stagnant.

Conclusion--Returning to the question presented at the beginning, we find that at the present time it can be only partly answered. We can say definitely that the Weather Bureau pan-to-lake coefficient has no outstanding value, although to say that it has no value whatever may possibly be a slight exaggeration. The design of this pan provides abundant opportunity for convection and heat leakage to make its reading so erratic as to cast serious doubt on its usefulness in view of the fact that if its coefficient cannot compete with a lake-to-lake coefficient, the pan coefficient is worthless.

There is no point in defending this pan on the ground that we do not have enough determinations of lake-to-lake coefficients, because a dearth of lake comparisons condemns the pan idea as much as the lake idea. Whatever merit a pan coefficient may have is derived from comparison with lakes.

A thermally insulated pan eliminates the heat leakage trouble, but if it is as small as the one used at Fullerton, it may still be somewhat erratic on account of convection caused by too low a water-surface temperature. This particular pan, which Young was kind enough to use, was provided by the writer for the purpose of finding out how it would act over a long period of time.

There are reasons for hoping that the BPI pan may have real value, and fortunately some strong evidence bearing on the question could be easily procured. Comparison of two of them, subjected to the same sky and atmospheric conditions, but one equipped with insulating material and the other not, would settle the heat leakage question. If heat leakage appeared to be absent, the experiment should, of course, be repeated at other places. The convection could easily be investigated with pans now in use. If the energy ratio [CUMMINGS, 1946] were determined at suitable intervals throughout the 24-hour cycle, over a period of two or three months, a comparison with corresponding determinations at other places would yield important information. An alignment diagram aids in the computation [CUMMINGS, 1930].

Young's work at Fullerton settles one aspect of the main question beyond doubt. There is no justification for continuing any particular pan merely because that pan has been used before. His results show clearly that all the pans are interchangeable with an error much smaller than that involved in any known pan-to-lake coefficient.

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[Because of the death of Mr. Young on July 8, 1947, two associates of Mr. Young were invited to prepare comments on Cummings' discussion. These closing comments follow... Ed.]

Carl Rohwer (Fort Collins, Colorado)--Cummings has raised the question whether pan evaporation records add anything to the knowledge of lake evaporation that cannot be obtained more readily and cheaply by other means. What will ultimately be possible in this respect it is impossible to say at the present time, but there is no doubt that more direct means of solving the problem will be found. Cummings has worked on the relation of insolation to evaporation and when the uncertainties of this method have been eliminated a direct solution will be available. In the meantime, however, it is believed that the coefficients established by Sleight, Young, and others, including the writer, serve a a very useful purpose in making it possible to provide a reasonable estimate of the evaporation from a lake based on evaporation pan records. It is true that recent studies have shown that the relation between pan evaporation and lake evaporation is not constant as was originally thought. Nevertheless, the information now available makes it possible to choose a coefficient suitable for the conditions where the comparison is to be made.

Harry F. Blaney (Los Angeles, California)--Since evaporation losses are of importance as an element affecting the net water supply available for irrigation of crops, for production of power, and for municipal and industrial uses, it is regretted that the paper by the late Arthur A. Young on "Some Recent Evaporation Investigations" did not create more discussion. The writer, who was associated with the author on evaporation studies for many years, will attempt to answer some of the questions raised by Cummings.

Cummings has offered some good suggestions. However, the writer does not agree with most of his conclusions. His opening paragraph indicates that he is discussing two previous reports by Young as well as the current paper. Thus, it may be rather difficult for most readers to follow the discussion unless they have access to the other two reports.

Cummings states that the Weather Bureau pan coefficient is worthless and casts doubts on most pan records. There has been a long-standing controversy among engineers, physicists, and hydrologists as to what is the best method for determining lake evaporation.

In California alone there are some 250 evaporation records available [YOUNG, 1947]. The first observation was made in 1881. Engineers and water-company superintendents have been using pan records to estimate lake and reservoir evaporation for over 65 years and they will continue to do so until some more reliable means are available. CUMMINGS [1930] made some excellent recommendations for improving evaporation measurements but unfortunately these suggestions have been considered only in a few locations. Engineers have recognized the fact that the Weather Bureau pan may not be the best device for measuring evaporation. In California State Bulletin No. 54, YOUNG [1947] states:

> Pan coefficients vary according to the size and exposure of the evaporation pan. The Weather Bureau pan is the least efficient as it has the highest rate of loss and the lowest coefficient. For pans set in the ground the largest are the most efficient and have the highest coefficients....
>
> ...Evaporation coefficients were determined that are applicable in estimating evaporation from large water areas from records of pans similarly located. Coefficients used should be those developed under climatic conditions closely similar to those existing where they are are to be applied...

A summary of evaporation coefficients as determined by various investigations in western states prepared by YOUNG [1947] is shown in Table 2.

Table 2--Summary of evaporation coefficients as determined by various investigations in Western States

Type or size of evaporation pan	Evaporation coefficients established by investigations at			
	Denver, Colorado, elevation 5300 ft [SLEIGHT, 1917]	Ft. Collins Colorado, elevation 5000 ft [ROHWER, 1931]	Milford, Utah, elevation 5000 ft [WHITE, 1932]	Fullerton, California, elevation 100 ft [YOUNG, 1947]
85-foot circular reservoir	...	1.00	...	...
Circular ground pans three feet deep				
Diameter, 12 ft	1.00	...	1.00	1.00
Diameter, 6 ft	0.92	...	...	0.91
Diameter, 4 ft	...	...	...	0.89
Diameter, 2 ft	0.78	...	...	0.81
Diameter, 1 ft	0.63	...	...	0.66
BPI pan	0.94	...	...	0.94
Colorado square pan	0.79	0.79	...	...
Weather Bureau pan	0.70	0.70	0.67	0.77
Two-foot diameter screened ground pan	...	...	...	0.98
USGS square floating pan	0.89	0.77	...	...

Cummings states that Young's entire investigation appears to have been planned from the point of view of a pan-to-lake coefficient, with special emphasis on the Weather Bureau pan. This was not the case as clearly indicated on the first page of the paper. There are over seven types of evaporation pans being used in California and the primary objective of the investigation was to determine suitable coefficients for all types of pans under Southern California climatic conditions.

Cummings implies "that the southwest coefficient applies in Intermountain country better than does the Intermountain coefficient." In reply YOUNG [1947] stated:

> In general, it may be presumed that coefficients obtained as a result of the investigations in Colorado are applicable to the region of the Intermountain States where winter temperatures are below freezing. Coefficients obtained in Southern California would appear to be applicable to the lower areas of the southwestern states where winters are short and mild. In California the Colorado coefficients probably apply to the higher mountain regions, while the Southern California coefficients are more suitable for the lower elevations of coastal and interior valleys.

The conclusions by Cummings on the value of pan coefficients seem to be based partially on his three months observations [CUMMINGS, 1946] at Bear Lake in 1937. That there may be some question about these results is indicated by the fact that the average seasonal Weather Bureau pan coefficient was reported [CUMMINGS, 1940] as 1.04 in 1940, while a revised study [CUMMINGS, 1946] of these observations in 1946 shows an average seasonal coefficient of 0.86. In his discussion Cummings compares the average coefficient of 0.86 for three months (July to September, inclusive) at Bear Lake with a five-month (May to September, inclusive) average coefficient of 0.77 at Lake Elsinore. Such a comparison might lead to erroneous results, as the three-month average at Elsinore is 0.80. A comparison of the monthly coefficients as determined by Cummings at Bear Lake and those determined by Young are shown in Table 3.

Table 3--Comparison of monthly coefficients as determined by CUMMINGS [1946] and YOUNG [1947]

Location	Determined by	July	August	September	Average
Bear Lake, Utah	Cummings	0.45	1.17	1.00	0.86
Lake Elsinore, California	Young	0.74	0.78	0.87	0.80

In 1919 the writer continued the study of SLEIGHT [1917] at Denver on evaporation from various sized pans. The pan coefficients for that year did not differ materially from those determined by Sleight in 1916 and 1917 (see Table 2). The writer has been associated with evaporation studies for about 30 years and has found evaporation pan records very useful in estimating evaporation and evapo transpiration losses in moist areas in connection with consumptive use of water investigations [BLANEY and MORIN, 1942]. The writer has also demonstrated the feasibility of estimating evaporation by correlating monthly temperature, per cent of daytime hours, and pan records [BLANEY, 1946].

The screened pan developed by Young is being used by several agencies in California and preliminary results indicate that this pan is more satisfactory for estimating reservoir evaporation than other pans now in common use.

Cummings' suggestion that a comparison be made between a standard BPI pan and one equipped with insulating material is excellent. It is hoped that some agency will undertake such an investigation. Insofar as the writer can determine, there are very few insulated pans, such as Cummings has used, now in operation.

Engineers usually can not wait years or even months for the results of experiments. Thus, they use the best data available. Long-period pan records are available at many places. Engineers will continue to use evaporation pan records and empirical formulas until such time as research workers can demonstrate the practicability of estimating evaporation from large bodies of water at many locations by the energy balance, the vapor-pressure gradient, or other methods.

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DISCUSSION OF

"EROSIONAL PHENOMENA ASSOCIATED WITH VOLCANIC ERUPTION OF PARÍCUTIN, MEXICO" by W. C. LOWDERMILK

[Trans., v. 28, pp. 269-270, 1947]

E. N. Munns (U. S. Forest Service, Washington 25, D. C.)--Erosion of the volcanic ash at Parícutin is proceeding at a rapid rate. Lowdermilk indicates how this takes place. Cutting is reported not only in the ash but also as extending downward into the original soil.

It is presumed that before the formation of the volcano the original soil was in balance with the rainfall. Hence, unless the land had been abused, not much erosion had taken place. Now, this older soil is being eroded despite a protective covering of ash.

The author believes that the precipitation in the area is now about the same as before the Volcano developed, and that the amount of water vapor contained in the eruptions was so small as not to cause added rain. His latter belief is probably true, but the former does not appear to

to be correct. It is known that convectional currents will bear aloft great masses of surface air, if there is a sustained source of heat. We have many times seen cumulus clouds develop over forest fires. These great fires are usually extinguished, not by man alone, but by rain. Similarly the great holocausts of big cities such as Chicago, San Francisco, and others were also rained out, perhaps due to convectional storms generated by the cooling of the constant, steady upward-borne stream of warm, humid air. Parícutin acts in the same manner. The temperatures are high, the heat is sustained, and an upward draft of air of great volume takes place. When this air reaches the colder air strata, the moisture is condensed into a cloud, which, when the right conditions prevail, produces rain.

It is to be expected therefore that with added precipitation of high intensities, erosion of the older soils will take place. It is also to be expected that when the Volcano cools and is no longer active, the number of convectional storms will decrease and the annual precipitation will markedly fall off.

DISCUSSION OF

"TRANSVERSE DISTRIBUTION OF SUSPENDED SEDIMENT BELOW RIVER CONFLUENCES" by ALBERT E. COLDWELL

[Trans., v. 28, pp. 747-751, 1947]

Billy T. Mitchell and James A. Constant (Corps of Engineers, Omaha, Nebraska)--Coldwell's paper is of considerable interest to the sediment engineer, and his statement that "heterogeneous currents... could determine the location of intake structures for water supply, navigation, irrigation, or other projects which depend to some extent on turbidity of water" is undoubtedly true. The restricted mixing of clear and silty water below the confluence of a clear stream and a muddy stream, which he observed, has often been noted in the past, but this characteristic usually disappears rapidly as the flow progresses downstream, especially in the case of turbulent streams.

The tables presented clearly demonstrate that, at Tulsa, the suspended sediment concentration is greater in general at the right bank sampling point than at the left. Coldwell states that this shows "that the Cimarron River has a tendency to retain its identity with reference to suspended sediment concentration even after flowing through 18 miles of channel below its confluence with the Arkansas River." Coldwell has presented no evidence that this transverse concentration gradient is not due to other causes. He has given no indication of the velocity or depth variations at the sampling points; neither has he given any indication of the size distribution or other physical characteristics of the suspended sediment. Of course, after the two streams have entered the same channel, they are acted on by gravitational forces in the same direction and, although there may be some tendency for the mixture with the higher specific gravity to creep under the lighter mixture, the mixing of the two streams will be dependent mainly on turbulence and helicoidal flow. In a fairly turbulent, sinuous stream, this intermixing should take place in a comparatively short distance while in a slow moving stream of considerable width, complete mixing might not take place for quite some distance downstream from the confluence of the two streams. It is difficult to conceive, however, that mixing would not have taken place within 18 miles unless the two streams ran in nearly separate channels or in a single fairly straight channel of great width.

One possible explanation of the color difference might be that there is a difference in the sizes of the suspended sediments carried by the two streams. If the red sediments were in the silt range and the brown sediments were in the clay range and the velocities at the left bank sampling station were considerably less than those at the right bank sampling station (the concentrations given indicate the probability of such a difference in velocities), there would be a considerable difference in the amount of silt (red material?) which would be brought to the surface. Concentration variations usually reflect differences in velocity and depth either at the station or a short distance upstream; and the higher concentrations near the right bank during high water indicate the presence of the thalweg at or near that point.

At Omaha, the Missouri River is under almost daily observation by personnel of the Corps of Engineers. A difference in color is sometimes noted as one crosses the river on the Ak-Sar-Ben Bridge. This color variation occurs most frequently during low water periods. During such periods the thalweg of the stream is against the right bank, and the velocities and depths, as well as the concentrations and average grain sizes of suspended sediment are considerably greater there than near the left bank. At higher stages the centroid of flow moves toward the left bank and there is a more nearly symmetrical distribution of depths, velocities, concentrations, and grain sizes about the center of the stream. Particle size analyses clearly indicate that these

variations in concentrations are due primarily to differences in the amount of the coarser sediments in suspension, the so-called "wash load" concentration remaining nearly the same throughout the cross section. The color of this wash load is usually different from that of the heavier sediments which are a buff color. The combination of the two types of sediment influences the color of the stream. During low water, the velocities near the left bank are so low that only the wash load is carried in appreciable quantities. The color of the stream consequently is the color of the wash load, and is often different from that portion of the stream which also carries larger amounts of coarse sediments. In the faster part of the stream "boils" are often noted. These boils carry large amounts of coarse material to the surface and are usually different in color than the surrounding stream.

At Omaha, on August 22, 1947, with a discharge of 42,600 cfs, it was noticed that the water from station 6+90 to the left bank (stationing is from right to left banks) was noticeably lighter in color than the rest of the stream. There was no appreciable concurrent flow from tributaries above Omaha which could affect the transverse sediment distribution at the sampling station. Samples are not usually taken in this portion of the cross section as it is nearer the left bank than the point where the third centroid is usually located. In this instance, however, a set of point samples were taken from this part of the stream in order that it might be compared with the rest of the stream. Samples were taken in nine verticals on this occasion. Five-point samples were taken at each vertical, except at station 7 + 10, where three-point samples were obtained because the depth was less than ten ft. These samples have been analyzed individually for sediment concentration, and the samples taken at stations 5 + 10 and 7 + 10 have had size-distribution determinations made by the bottom-withdrawal method. The average concentration, average velocity, and depth at each vertical are shown in Table 1.

Table 1--Data on sediment in the Missouri River at Omaha, Nebraska

Station	Average concentration	Total depth	Average velocity
	gm/liter	ft	ft/sec
1+05	2.263	16.0	1.6
1+60	2.280	18.4	3.2
2+15	2.322	18.2	4.4
2+60	2.521	20.0	5.4
3+10	2.435	22.2	6.2
3+60	2.307	12.6	6.4
4+25	2.482	15.0	6.0
5+10	2.176	16.5	4.8
7+10	1.591	7.5	0.8

The size distributions and concentrations of the various samples from the two verticals nearest the left bank are shown in Table 2. It will be noted that the average total concentration at station 7+10 is 73 per cent of that at station 5+10, and although the clay concentration is 86 per cent and the silt concentration is 75 per cent, the sand concentration is only 27 per cent of that at station 5+10. After size analyses were made of the samples taken at stations 5+10 and 7+10, the residues were inadvertently disposed of and as no color comparisons were made. However, since the samples taken in the other verticals were still intact, those from stations 1+05, 2+15, 2+60, 3+60, and 4+25 were composited and separated by decantation into the three categories: sand, silt, and clay. The clay was a light buff color, the sand a darker buff color, and the silt a darker buff than either the sand or the clay. A further examination of the clay showed that the lighter colloidal matter was almost yellow. It appears, therefore, that the difference in color noted in the stream is attributable to the predominance of certain sediments, which in turn is determined by the hydraulic conditions prevailing in that part of the channel.

Table 2--Size distributions and concentrations of sediment samples

Station	Depth taken	Total concentration	Sample			Concentration of fractions		
			Clay	Silt	Sand	Clay	Silt	Sand
	ft	gm/liter	pct	pct	pct	gm/liter	gm/liter	gm/liter
5+10	1.4	1.875	55	37	8	1.032	0.693	0.150
	4.3	2.035	58	28	14	1.180	0.570	0.285
	7.2	2.125	45	36	19	0.956	0.765	0.404
	10.3	2.462	45	32	23	1.109	0.787	0.566
	14.3	2.381	47	28	25	1.120	0.666	0.595
Average		2.176				1.080	0.696	0.400
7+10	1.5	0.727	66	26	8	0.480	0.189	0.058
	4.4	1.917	63	32	5	1.208	0.613	0.096
	5.9	2.130	52	40	8	1.107	0.853	0.170
Average		1.591				0.932	0.552	0.108

This color difference has been noted several times in the past but this was the only instance known to the writers in which an attempt was made to analyze and explain the phenomenon. Although the hypothesis presented herein is not supported conclusively by the available data, it appears to be worthy of submission in a discussion of color and concentration variation in streams.

Albert E. Coldwell (Corps of Engineers, Tulsa, Oklahoma, Author's Closure)--Mitchell and Constant have presented some aspects of the transverse distribution of suspended sediment that show the need for amplification of the original paper.

The Arkansas River between the mouth of the Cimarron River and the Tulsa gage approaches the condition of "a fairly straight channel of great width" mentioned by Mitchell and Constant. Its channel consists of four gentle curves interconnected by three tangents, and is between 1000 and 2000 ft wide. Its direction is not changed more than 90 degrees by any of the curves. A highway parallels the river on a bluff for several miles, and the color variation has been noted from the highway as well as from the bridge where the samples were collected.

From the concurrent data available at the time the samples were collected, it appears that the depths at the sampling points might have a slight, though possibly insignificant, effect on the concentration results. For the 38 tests shown in the author's Table 2 the water ranged from 2.5 ft to 20.0 ft in depth. The tests, when averaged, gave the following depths: Left bank 9.45 ft; center 9.60; and right bank 9.99 ft.

Velocities were obtained for only 33 of the 38 tests and do not show any appreciable trend. These ranged from 0.30 to 9.18 ft per second, with averages as follows: Left bank 3.90 ft/sec; center 3.38 ft/sec; and right bank 3.99 ft/sec.

There are no data available as to grain-size variations for specific tests across the Arkansas River at Tulsa, but as shown in Table 3, herewith, there is not much difference in the grain size of suspended sediment in the Arkansas and Cimarron Rivers above their confluence.

Table 3--Average grain size of suspended sediment

River	Station	No. of tests	Sample		
			Sand	Silt	Clay
			pct	pct	pct
Arkansas	Ralston	10	15	40	45
Cimarron	Mannford	13	15	44	41

One case is available in which grain-size analyses were made on the same day, March 26, 1945, at Ralston, Mannford, and Tulsa, with results as shown in Table 4. It will be noted that this comparison makes no allowance for time of travel.

Table 4--Grain sizes above and below confluence of Cimarron and Arkansas Rivers

Station	Discharge	Sample		
		Sand	Silt	Clay
	cfs	pct	pct	pct
Ralston	27,200	16	51	33
Mannford	7,990	9	48	43
Tulsa	41,400	14	45	41

DISCUSSION OF

"FORECASTING COLORADO RIVER FLOW" by J. W. STANLEY and R. E. KENNEDY

[Trans., v. 28, pp. 766-779, 1947]

L. R. Beard and G. B. Levin (751 Figueroa St., Los Angeles, California)--The problem of forecasting Colorado River flow into Lake Mead has occupied the writers of this discussion for the past 15 months. During that period all available methods of forecasting Colorado River flow were carefully studied, and practically all of the authors of these methods were interviewed personally.

Stanley and Kennedy have devised a particularly fine forecasting procedure. Its advantages are the ease of obtaining data in time for a forecast, the simplicity of preparing the forecast, and the over-all accuracy of the February 1, March 1, April 1, and May 1 predictions, which compare very favorably with the accuracy of other methods.

There is a reasonable question as to whether the true correlation coefficients are as high as those indicated in the analysis. It appears that the selection of 13 specific precipitation stations because of their high individual and group correlation with runoff is not an unbiased statistical selection and that the computed coefficient of correlation may be considerably higher than the true one. Mordecai Ezekiel in his Methods of Correlation Analysis makes the following statement (second edition, p. 324): "If the several independent variables in the multiple correlation had been selected by considering a large number of possible independent variables, and by retaining only those which showed the highest gross or net correlation with X_1, there is a much larger possibility of the correlation in the sample exceeding the true correlation in the universe by a wide margin. In fact, it is almost certain to be erroneously high."

In order to obtain an objective estimate of precipitation over the basin, the writers used data of 45 precipitation stations whose records were long enough to be useful, and weighted the data in accordance with the runoff fraction contributed by each basin. This result was correlated with runoff, and a value for the correlation coefficient on May 1 of 0.768 was obtained. This figure should be compared with 0.896 quoted by the authors. The difference is very significant since the coefficient of determination in one case is 0.590 and in the other case 0.803. This difference may be due to accidental correlations as discussed by Ezekiel, or to inherent natural relationships, or, more likely, to a combination of these factors. It appears that the true correlation coefficient is considerably less than 0.896. The real proof of the method will be the forecast verification during ten or 20 years. So far, the actual forecasts made by Stanley and Kennedy have been exceptionally good.

The authors made the following statement (p. 769): "It appears, then, that the trend has been fairly well established by May 1 as far as precipitation is concerned, and that later precipitation is only a minor cause of error in the forecasts. Other variables as yet undiscovered would appear to be mainly responsible for the difference between predicted and actual runoff." From a logical point of view, the unpredictability of May-through-July precipitation should result in more than a minor error. This would be especially true with a late snow melt and an unusually heavy May-through-July precipitation where a great deal of rain could be caught in the snow cover. A correlation involving runoff versus October-through-April precipitation for the 45 stations mentioned above and May-through-July precipitation for these same stations yielded a beta coefficient (in per cent) for October-through-April precipitation of 73 per cent and one of 27 per cent for May-through-July precipitation. This indicates that in the correlation the importance of May-through-July precipitation is 37 per cent as much as that of October-through-April precipitation. Stanley and Kennedy mention that even if May-through-July precipitation were known and used as a third variable the coefficient of correlation would change only from 0.896 to 0.916. Actually, a slight change in a high correlation is significant, for the coefficient of non-determination ($1-r^2$) in the first case would be 0.197 and in the second case 0.161. The inclusion of May-through-July precipitation has reduced the remaining error by 18.3 per cent. As a matter of fact, studies made by the writers indicate that errors as large as 1,000,000 ac ft can be attributable to May-July precipitation in extreme years.

I. W. Stanley and R. E. Kennedy (U. S. Bureau of Reclamation, Boulder City, Nevada, Author's closure)--The authors appreciate the thoughtful comments of Beard and Levin. With reference to the method of selecting precipitation stations for use in forecasting, they cite the warning by Ezekiel against retaining in a multiple correlation only those variables that give the higher correlations. While this study did not use the multiple correlation method but rather the accumulating average of station records, it is true that precipitation stations were selected because of their high individual correlations with runoff. Beard and Levin suggest that this "is not an unbiased statistical selection," and that therefore the correlation may be fictitiously high.

The authors believe there is considerable merit in their method of selecting stations. Runoff must come from precipitation, and therefore those stations that give the highest correlation between the two phenomena should be the logical ones to use, particularly in view of the generally accepted theory that if all available stations are to be considered, some must either be adjusted appreciably to make them suitable for use, or be thrown out entirely.

It would seem that the real test would be how the functions that depend on the correlation, such as the error of the estimate, meet the requirements of the normal curve. It may be seen from

Figure 8A in the paper that errors of the estimates over the 32-year period meet the requirements of the normal curve in that three estimates (one for every ten) fall outside the 9:10 limites in the 32 years of record. As for the forecasts actually made for 1946 and 1947 being exceptionally good, the authors labor under no delusion as to the efficiency of the method. As shown by Figure 8A, the actual runoff is almost certain to differ from the mean forecast by 2.2 million ac ft, or more, once in ten years on the average; and in nine out of ten years it may differ anywhere from zero to 2.2 million ac ft.

Beard and Levin state also, "The unpredictability of May-through-July precipitation should result in more than a minor error. This would be especially true with a late snow melt and an unusually heavy May-through-July precipitation where a great deal of rain could be caught in the snow cover. ...As a matter of fact, studies made by the writers indicate that errors as large as 1,000,000 ac ft can be attributable to May-July precipitation in extreme years." There is no question that appreciable runoff can result from May-July precipitation in extreme years. However, it would seem that if this condition occurred frequently, a much larger difference in the coefficient of correlation should have resulted when the May-July precipitation was added as a third variable. The fact that the correlation changes so little would seem to be proof that the above condition does not occur often. The change in the "r" from 0.896 to "R" = 0.916 results in a change in the 0.9 error of the estimate from 2.3 million ac ft to 2.05 million ac ft, a reduction of about eight per cent.

During the two years since the paper was written work has continued on investigation of the forecasting problem. Many new approaches have been made, and additional variables and combinations of variables have been tried in attempting to improve the forecast method. To date this work has not justified any change in the basic method of forecasting. The 13 key stations are still used. A slight reduction in forecast range has been realized, however, by certain refinements such as adjustment of early runoff records by the double mass-diagram method. Research is being continued, and other approaches are being investigated.

Corrigenda--The following corrections are noted in this paper as published: (1) p. 774 in Fig. 4C the reference should be to Table 5, not Table 4; (2) p. 779, the address of the authors is Boulder City, Nevada, not Colorado.

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NOTES AND PERSONALIA

NOTES

Sixteenth Congress of the International Geographical Union--The Sixteenth Congress of the International Geographical Union will be held in Lisbon, Portugal from September 21-29, 1948. This is the first meeting to be held following the War, and it is anticipated that attendance will be very good from many adhering countries. Persons interested in attending from the United States should get into touch with George B. Cressey, Chairman of the National Committee of the United States, at Syracuse University, Syracuse 10, New York, or directly with the Organizing Committee, Praco do Rio de Janeiro 14, Lisbon, Portugal.

Fourth Pan American Consultation on Cartography--The Fourth Pan American Consultation on Cartography will be held in Buenos Aires this fall. Scientific sessions will extend from October 15 to November 4, 1948. The period from November 4 to November 14, 1948 will be taken up by excursions to various points in Argentina.

International Bibliography of Geodesy--The International Bibliography of Geodesy, normally published triennually to provide a careful and detailed classification of all works and articles dealing with geodesy and closely related subjects, is resuming publication after interruption during the War. Volumes I-III were published before the War and carry the bibliography through 1937. Volumes IV and V, carrying the record through 1945, should be available soon. Orders may be placed directly with the Bureau Central de l'Association de Géodésie, 19, rue Auber, Paris-IX^{e}, France, or through Walter D. Lambert, American member of the Permanent Council, in care of the American Geophysical Union. The price delivered in this country is $6.50.

Gravity-measuring cruise--H. M. submarine Trident conducted a two-weeks' cruise of the English Channel from Plymouth to Hastings in May 1948, during which gravity measurements were carried out by B. C. Browne, R. I. B. Cooper, and R. L. G. Gilbert of Cambridge, University.

Launching of Velero IV--The new floating laboratory of the Allan Hancock Foundation for Scientific Research of the University of Southern California was launched by Barbara Louise Fagg at the National Iron Works, San Diego, on April 11, 1948. Velero IV is a 110-foot steel motorship, displacing 510 tons, and in general design resembles the large West Coast vessels of the tuna industry. Allan Hancock, Director of the Foundation, will also be master of Velero IV.

Commissioning of Albatross III--The Fish and Wildlife Service research vessel, Albatross III, was commissioned at Boston Fish Pier on March 19, 1948, by J. A. Krug, Secretary of the Interior. Carrying on an honored name in United States fishery investigations, the 180-foot vessel was originally the diesel trawler Harvard. She was donated to the federal government by the New England

fishery industry before the War, but her conversion was delayed while she served in the Coast Guard as a patrol vessel. The Albatross III will be based at Woods Hole, Massachusetts.

French polar research--Two French polar expeditions are being organized under the direction of Paul-Emilie Victor. One was scheduled to sail in May 1948 for Greenland waters in the oceanographic vessel President Theodore Tissier. The other will proceed later in the year to Adelie Land, Antarctica. Plans are also underway for the establishment of meteorological observatories on the islands of Kerguelen, Crozet, Marion, Amsterdam, and St. Paul in the approaches to the Antarctic.

Sale of Discovery II--Recently serving in the Thames Estuary for Trinity House, the former research vessel Discovery II has been bought by the Irish Lights Board.

Standard sea water--The International Association of Oceanography has assumed responsibility for the supply of Copenhagen Standard Sea Water, which will continue to be prepared under the direction of Martin Knudsen of the Danish Hydrographic Laboratory.

American Society of Limnology and Oceanography--The Limnological Society of America was reorganized on March 1, 1948 to include research in marine environments as well as lakes. G. L. Clarke of Harvard University is secretary-treasurer of the new society.

New meteorological publication--A new publication, Zeitschrift für Meteorologie, successor to Meteorologische Zeitschrift which suspended publication in July 1944, has put in its appearance as a monthly publication starting with October 1946. R. Süring of the Potsdam Meteorological Observatory (Soviet Occupation Zone) is the editor, and communications concerning it should be addressed to him. Magnetic, hydrologic, and other geophysical papers are printed in the publication as well as those relating to meteorology.

California state fisnery vessels--The N. B. Scofield was recently returned to the State of California Division of Fish and Game from her war service, and will soon be ready for sea after reconditioning. She will be supplemented in 1949 by additional recently authorized craft.

Reappearance of Meteorological Magazine--Meteorological Magazine, a British publication that ceased publication in June 1940 after nearly 75 years, has resumed as of January 1947. It retains its former nature as an interpretation of meteorology for laymen, but includes the first reporting of important work which makes it of great value to the scientific meteorologist as well. Those interested in subscribing should get into touch with the British Meteorological Office, London, England.

German Hydrographic Journal--The first issue of the German Hydrographic Journal was received in the United States in March 1948. It is published by the German Hydrographic Institute of Hamburg under the authority of the Allied Control Council and is edited by A. Schumacher. The field of interest includes coastal and open sea surveying, nautical science and technics, navigation and chronometry, terrestrial and ship's magnetism, and physical and chemical oceanography (including marine sediments). An ultimate aim is gradually to list all German and other publications of relevance that have appeared since September 1939.

PERSONALIA

C. A. Barnes of the University of Washington Oceanographic Laboratories, visited Ladd Field, Fairbanks, and the Arctic Research Laboratory, Point Barrow, in April and May 1948, making the trip north by the Stork Baker weather flight of the Air Weather Service.

Lloyd V. Berkner, head of the Section of Ionosphere Research at the Department of Terrestrial Magnetism, Carnegie Institution of Washington was recently elected to membership in the National Academy of Sciences for his outstanding work in ionospheric and upper air research.

Archie N. Carter, until recently Associate Editor of the Engineering News-Record and Construction Methods, has been named Manager of the Highway Contractors' Division of the Associated General Contractors of America.

B. G. Escher of the University of Leiden, Leiden, The Netherlands, has been named Acting President of the Association of Vulcanology, IUGG, succeeding A. Michel-Lévy of France who is in poor health.

Maurice Ewing, Professor of Geophysics at Columbia University, was recently elected to membership in the National Academy of Sciences for his outstanding work in oceanography and in geophysics generally.

A. H. Glenn, formerly with the Air Weather Service, has opened an office in New Orleans as a consultant in meteorology and oceanography in connection with the offshore-drilling work in the Gulf of Mexico.

Columbus O'D. Iselin, Director of Woods Hole Oceanographic Institution, has been given the Medal of Merit of the National Research Council for "exceptionally meritorious conduct in the performance of outstanding services to the United States from 1940 to 1946."

Risto Jurva has been appointed Director of the Institute for the Exploration of the Sea in Helsinki, effective June 1, 1947.

Ralph L. Parshall, Irrigation Engineer of the U. S. Department of Agriculture at the Colorado Agriculture Experiment Station, has been elected the General Chairman of the Western Snow Conference, succeeding Wayne D. Criddle.

R. R. Revelle has been appointed Associate Director of the Scripps Institution of Oceanography of the University of California.

Gustaf Slettenmark, Director of the Swedish Meteorological-Hydrographic Service, has been named Acting President of the Association of Scientific Hydrology, succeeding Otto Lütschg who has died.

Isidore I. Broman, petroleum geologist of Austin, Texas, died on March 24, 1948. He was born in Kent City, Michigan in 1883, and received his baccalaureate and masters degrees from Augustana College in 1908 and 1917, respectively. In 1917 and 1918, he was Professor of Geology at Augustana College. Following that, he held positions on geophysical and geological exploration work for several oil companies, finally establishing himself as a consulting petroleum geologist.

Nelson Horatio Darton, for many years geologist with the U. S. Geological Survey, died February 27, 1948 at the age of 82. He was born in New York, N. Y. in 1865, and devoted his entire professional career to the work of Geological Survey, from 1886 to his retirement, except for the period from 1910 to 1913 with the Bureau of Mines. He was instrumental in development contour mapping and accurate map making, and was at one time in charge of the Western Division of ground-water investigations of the Survey. He was the author of several books and many other publications.

H. G. Fourcade, geophysicist of Witte Els Bosch, South Africa, died January 19, 1948.

Akitune Imamura, Japanese seismologist, died January 1, 1948.

Alfred Church Lane, Emeritus Professor of Geology at Tufts College, died suddenly on April 15, 1948 in New York where he had gone to join in the welcome to the returning Finn Ronne Expedition. He was born in Boston, Massachusetts, January 29, 1863. He received his baccalaureate degree from Harvard in 1883 and his doctorate in 1888. From 1883 to 1885, he was Instructor of Mathematics at Harvard, and following his receipt of the doctorate, he entered the service of the U. S. Geological Survey, following which, he undertook work with the Michigan Geological Survey, and was the State Geologist from 1899 to 1909. He then became Pearson Professor of Geology and Mineralogy at Tufts College, which post he held until he retired in 1935. In his retirement, he continued to be active, taking part in the activities of the National Research Council and various scientific societies. It was anticipated that he would present the last paper in the Symposium of The Earth's Crust, at the Twenty-Ninth Annual Meeting of AGU. His death occurred nine days before, and the Symposium has now been dedicated to his memory.

R. H. Montgomery, Chief of Levelling Division of the Geodetic Service of Canada was killed in October 1947 when his car was hit by a train near Broadview, Saskatchewan. He did much to advance the vertical control work in Canada. A paper reporting his findings along the Alaska Highway appeared in the issue of the Transactions of February 1948.

Harold Bernard Ward, Assistant Professor of Geography, Northwestern University, died January 4, 1948. He was born at Mt. Pleasant, Michigan, October 10, 1889, and received his baccalaureate and doctorate degrees from the University of Chicago in 1915 and 1934, respectively. In 1915 he began his career as Assistant Professor of Geography at George Peabody College for Teachers, continuing in 1916 and 1917 at Central State Teachers College. He served as a Captain in the U. S. Army during World War I, following which he began his work at Northwestern University.

TWENTY-NINTH ANNUAL MEETING (1948)

MINUTES, GENERAL ASSEMBLY AND SECTIONS

EVENING SESSION AND SYMPOSIUM

The Evening Session of the American Geophysical Union was called to order by President Oscar E. Meinzer at 20^h10^m, Wednesday, April 21, 1948, in Elihu Root Hall, Administration Building, Carnegie Institution of Washington, 1530 P Street, Northwest, Washington, D. C. About 225 were in attendance. After preliminary remarks, President Meinzer turned the Chair over to Merle A. Tuve who presided as Chairman of the Symposium. This was the first of two sessions of the Symposium on the Earth's crust; four papers were presented as follows:

(1) M. H. Gilmore: Relation of microseisms to meteorology
Discussion by B. Gutenberg
(2) E. A. Johnson: Pre-history of the Earth's magnetic field
(3) M. Ewing: Structure of the Mid-Atlantic Ridge
(4) Frank Press: Ocean-bottom structure from seismic observations

There was also brief discussion from the floor, following each presentation.

Chairman Tuve mentioned that the second session of the Symposium would be held Friday, April 23, 1948, in the Auditorium of the Natural History Building at 14^h00^m. He remarked that Alfred C. Lane, who was to have given the final paper of the Symposium, had died suddenly on April 15, 1948. After paying tribute to the long and outstanding career of Professor Lane, he suggested that the Symposium be dedicated to the memory of Professor Lane. A motion was made, seconded, and unaminously passed. Chairman Tuve declared that the Symposium would henceforth be called the Alfred C. Lane Memorial Symposium on The Earth's Crust.

The Chair was then returned to President Meinzer who introduced Leo O. Colbert who read the citation of the Tenth William Bowie Medalist (J. B. Macelwane) [see pp. 303-304 of this issue for citation]. Following this, President Meinzer presented the Medal to Dr. Macelwane, whose response is set forth on page 304-305 of this issue.

The session was then declared adjourned, and a social hour, with refreshments, followed in the adjoining room.

SPECIAL EVENING SESSION

After the publication of the program, arrangements were made for a Lecture Session to be given by Commander and Mrs. Finn Ronne who returned on April 15, 1948 from a 15-month sojourn to the Antarctic. The session was held in the Auditorium of the Natural History Building of the National Museum, Washington, D. C. President Meinzer called the meeting to order at 20^h15^m. About 225 were in attendance.

Commander Ronne gave a very interesting account of the trip to and from Palmer Peninsula and their stay there through a full year. The latter part of his talk was a running account accompanying a film taken on his last previous trip to the Antarctic. Following this, President Meinzer introduced Mrs. Ronne who gave a colorful account of the Antarctic from the woman's point of view. Mrs. Ronne is one of the first two women ever to winter in the Antarctic.

After a brief question period, the session adjourned at 22^h05^m.

AFTERNOON SYMPOSIUM AND BUSINESS SESSION

The afternoon Symposium and Business Session was called to order by President Meinzer at 14^h00^m, Wednesday, April 23, 1948, in the Auditorium of the Natural History Building of the National Museum, Washington, D. C. About 140 were in attendance. After opening remarks, President Meinzer turned the Chair over to Merle A. Tuve, Chairman of the Symposium on The Earth's Crust.

Chairman Tuve noted that this was the second session of the Symposium on The Earth's Crust, and that at the first session this Symposium had been dedicated to the late Alfred C. Lane who was to have been the last speaker on the program. The following papers were heard.

(1) William D. Urry: The significance of radioactivity in geophysics
Discussion by John P. Marble
(2) Fred B. Phleger, Jr.: Origin and rate of deposition of deep-sea sediments
(3) Arthur Knox: Fossil pollen and paleoclimatology
(4) E. A. Eckhardt: Tides in the Earth's crust
(5) N. Ricker: Attenuations and amplitudes of seismic waves
(6) John H. Hodgson: Use of rockbursts in the study of crustal structure
(7) R. W. Goranson: Effect of pressure on physical phenomena in the crust
(8) George P. Woollard: Nature of the crust from gravity anomalies
Discussion by Ross Gunn
(9) H. A. Marmer: Sea-level changes along the coasts of the United States in recent years

In addition to the formal discussion listed, there was informal discussion from the floor.

After paying a final tribute to Professor Lane, Chairman Tuve turned the Chair over to President Meinzer who then proceeded with the Business Session as follows:

The minutes of the Twenty-Eighth Annual Meeting were published in the June 1947 issue of the Transactions, and as no corrections had been received, they were declared approved as published.

General Secretary Beij summarized matters since the Twenty-Eighth Annual Meeting. These ar repeated in detail in connection with the minutes of the meeting of the Executive Committee of November 28, 1947 [see February 1948, Trans., pp. 142-149] and April 28, 1948 [to be published in the August 1948 issue of the Transactions]. Only to be especially noted is the great growth of the membership of the Union, due to the activity of Chairman H. F. Johnston and his Committee on Membership. The following is the summary for the period:

Members, April 27, 1947	2966	
Inactive to active status	5	
New members	1460	
New corresponding member	1	
Reinstated	1	
		4433
Active to inactive	2	
Resignations	101	
Deceased	12	
Dropped	28	
		143
Membership as of April 20, 1948		4290

The Annual Report of the General Secretary was accepted, with thanks.

Reports of Standing Committees

Meetings--Chairman John Putnam Marble of the Committee on Meetings presented a brief report (see Appendix A).

Nominations--Chairman James B. Macelwane of the Committee on Nominations stated that there are no immediate matters pending before the Committee, but that early in 1949 plans will be made for the triennial elections of 1950.

Budget--Chairman Herbert N. Eaton of the Committee on Budget outlined the budget briefly that was submitted to the Executive Committee on April 24, 1948. The report will be published with the minutes of the Executive Committee, to be published in the issue of August 1948.

Editorial and Publications--Chairman K.Hilding Beij of the Editorial and Publications Committee reviewed the past year briefly, pointing out that until July 1, 1947, the Transactions had been published in an edition of 3500 copies. Starting with the August issue of 1947, the edition was increased to 4500, because of the rapid growth in membership, and beginning with the first issue of 1948, the edition was increased to 5200. He mentioned also a substantial increase in printing costs, beginning with the December 1947 issue.

It was approved that the above reports be received and placed on file.

Reports of Special Committees

Resolutions--Chairman Earl Engerson presented the report of the Committee on Resolutions. The following eight resolutions were read and unamimously adopted:

(1) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The Smithsonian Institution, the Carnegie Institution of Washington, the United States Public Buildings Administration, and the National Academy of Sciences have kindly made available, meeting rooms and other facilities for the 29th Annual Meeting of the American Geophysical Union, and

WHEREAS, The Carnegie Institution of Washington also made available facilities for a special meeting of the Union at an earlier date, therefore be it

RESOLVED, That the American Geophysical Union express its deep appreciation of the kind action of these agencies, and instruct its General Secretary to express the thanks of the Union to the appropriate officers of each agency.

(2) RESOLUTION OF THANKS TO THE CARNEGIE INSTITUTION OF WASHINGTON

WHEREAS, The Carnegie Institution of Washington has for many years kindly furnished office and storage space and other facilities without charge for use by the American Geophysical Union, and has continued the same services during the past year, and

WHEREAS, The efficient and effective functioning of the American Geophysical Union has been made possible largely by these services, therefore be it

RESOLVED, That the American Geophysical Union express its sincere appreciation of this kind and generous action of the Carnegie Institution of Washington, and instruct its General Secretary to express the thanks of the Union for the same, to the President and Chairman of the Board and Trustees of the Carnegie Institution of Washington.

(3) RESOLUTION ON TIME SIGNAL SERVICE

WHEREAS, There is a vital need in all astronomical, geodetic, magnetic, and seismological work for accurate time service, and

WHEREAS, The time service maintained by the United States Naval Observatory, the Naval Communications Service, and the National Bureau of Standards has been of great use in this work, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of this valuable scientific cooperation, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of Naval Communications, the Superintendent of the Naval Observatory, the Secretary of Commerce, and the Director of the National Bureau of Standards.

(4) RESOLUTION OF APPRECIATION TO THE RONNE EXPEDITION

WHEREAS, The Ronne Expedition has established in Antarctica a seismic station, and

WHEREAS, This station has been of great value to Seismology, therefore be it

RESOLVED, That the American Geophysical Union express its thanks to the Expedition for the establishment of the said station and recommend its continuance, and be it further

RESOLVED, That a copy of this resolution be sent to the Leader of the Ronne Expedition.

(5) RESOLUTION ON NAVY SEISMOGRAPH STATIONS

WHEREAS, The Navy has established special seismograph stations in the Caribbean and Pacific areas, and

WHEREAS, These stations record many strong earthquakes, and

WHEREAS, These records would be of value in locating the epicenters, therefore be it

RESOLVED, That the American Geophysical Union request that, if possible, standard time control be furnished at the Navy Microseismic Station, and be it further

RESOLVED, That a copy of this resolution be sent to the Chief of Naval Operations.

(6) RESOLUTION ON EXTENSION OF GRAVIMETRIC NET

WHEREAS, A project has been submitted to the Office of Naval Research, Navy Department, to extend a gravimetric net over such parts of the United States as have not yet been covered by gravity observations, and

WHEREAS, This project when completed will be of very great value to the geophysical sciences, and

WHEREAS, This project has not yet been approved or authorized, therefore be it

RESOLVED, That the American Geophysical Union express its approval of this project

and urge the Director, Office of Naval Research to take favorable action concerning it, and be it further

RESOLVED, That copies of this resolution be sent to the Director, Office of Naval Research, and to Dr. George P. Woollard, Princeton University.

(7) RESOLUTION OF MEASUREMENT OF GRAVITY AT SEA

WHEREAS, Through the cooperation of the Office of Naval Research, Navy Department, and the Commander, Submarine Force, U. S. Atlantic Fleet, the measurement of gravity at sea has been further extended on the continental margin between Cape Sable and Cape Hatteras; off the west coast of South America between Panama and Valparaiso, Chile; off the north shore of South America between Panama and Trinidad; and in several locations in and around the Bahamas, and

WHEREAS, A part of the scientific expense of this work was borne by the Office of Naval Research which has underway an extensive program for the measurement of gravity at sea, by contract with Columbia University, and

WHEREAS, A part of the scientific expense of the work was met by the Penrose Fund of the Geological Society of America, and

WHEREAS, The basic instrumental equipment, the Vening Meinesz pendulum apparatus and a Bell Telephone Laboratories crystal chronometer, was supplied by the Woods Hole Oceanographic Institution, and

WHEREAS, Additional apparatus was furnished by Professor Vening Meinesz and by Columbia University, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of this valuable cooperation between the Navy Department and the private organizations and individuals connected with the project, and be it further

RESOLVED, That copies of this resolution be sent to the Director, Office of Naval Research; the Commander, Submarine Force, U. S. Atlantic Fleet; the commanding officers of the submarines engaged on this work; the President of Columbia University; the Director, Woods Hole Oceanographic Institution; the Geological Soceity of America; Professor Vening Meinesz; and to Dr. Maurice Ewing and the other members of the scientific party engaged in this work.

(8) RESOLUTION ON GEOPHYSICAL DATA OF COMMERCIAL COMPANIES

WHEREAS, The International Union of Geodesy and Geophysics at its Seventh General Assembly, held in Washington in September 1939, expressed the opinion that an agency should be designated in each member country where geodetic and geophysical work is done by petroleum and mining companies, to secure from these companies geodetic and geophysical data which may no longer be of commercial and economic value to them and that, since these data would be of great scientific importance, it is to be hoped that the various national agencies will make efforts to secure and use the data thus made available, and

WHEREAS, The United States Coast and Geodetic Survey is already charged with the development of the basic system of gravity stations in this country and has already secured a considerable quantity of additional gravity data from companies engaged in geophysical prospecting, most of which are still classified as confidential, therefore be it

RESOLVED, That the American Geophysical Union urge all petroleum companies, mining companies, and geophysical prospecting organizations to forward to the United States Coast and Geodetic Survey all gravity data which may be of value, subject to agreement on the part of the Coast and Geodetic Survey that such data or information will not be released to the economic disadvantage of the companies or organizations to which the data belong, and be it further

RESOLVED, That the American Geophysical Union express the hope that the companies which have already deposited or may in the future deposit confidential data with the United States Coast and Geodetic Survey will remove the confidential classification on these data, either wholly or in part, as soon as possible in order that these valuable data may be made available for general scientific use, and be it further

RESOLVED, That copies of this resolution be sent to the appropriate Federal Officials and to such commercial companies as may now or later be in a position to contribute gravity data for use in the furtherance of the geophysical sciences.

Cooperation with International Commission for Study of Tidal Waves--Chairman Martin A. Mason, who could not be present, submitted the report presented in Appendix B.

Geophysical and Geological Study of Continents--Chairman George P. Woollard presented the report shown in Appendix C.

Cosmic-Terrestrial Relationships--Chairman Harlan T. Stetson summarized the report presented in Appendix D.

Award of the William Bowie Medal--Chairman Leo O. Colbert embodied his report in the citation given on the opening pages of this issue.

It was approved that the above reports be received and placed in file.

Adjournment--The meeting was adjourned at 17h12m.

Sessions of Sections

The minutes of the meetings of the Sections are found in Appendices E to L.

APPENDIX A--REPORT OF THE COMMITTEE ON MEETINGS

John Putnam Marble, Chairman

J. A. Duerksen	O. W. Torreson	Frank J. Veihmeyer
Nicholas A. Rose	Merle A. Tuve	George G. West

Two regional meetings have been held during the past 12 months: The Twenty-First in the New England area in September 1947, sessions being held at Middletown, Connecticut; Cambridge, Massachusetts; and Woods Hole, Massachusetts; the Twenty-Second in California in February 1948. Reports of these have previously appeared in the Transactions.

The Twenty-Ninth Annual Meeting was held at Washington, D. C. on April 21, 22, and 23, 1948, sessions being held in the National Academy of Sciences, the Interdepartmental Auditorium, the United States National Museum, and the Carnegie Institution of Washington. The registered attendance was in excess of 800. In addition to meetings of all Sections, there was held a two-session symposium on "The Crust of the Earth" under the Chairmanship of Merle A. Tuve; an evening lecture on "Scientific Work of the Finn Ronne Antarctic Expedition," with additional matter concerning the organization, running, and general results, by Commander and Mrs. Finn Ronne; the award of the William Bowie Medal to James B. Macelwane; and an informal smoker.

In accordance with views previously expressed by members residing outside the Washington area, furthered by discussions with the Officers, Section Officers, and Executive Committee of the Union, plans are being drawn up to facilitate the holding of further regional meetings. The first step, a detailed study of the geographical distribution of the membership is nearly complete.

Your Committee envisions: (1) A continuance and furthering of its present character as representing various regions of the country where there is a moderate concentration of membership; (2) the setting up (either ad hoc or on a continuing basis) of one or more representatives of each section on a similar basis; (3) the division of the country into regions, of a flexible nature, within the boundaries of which regional meetings might well be organized.

With such arrangements, the organization of a regional meeting should prove reasonably simple, and the work of the local committee be not over-difficult. It should be borne in mind that the call for such a meeting should come from the members in the region, and not be imposed from outside; that because of the time required to prepare adequate papers and the many conflicts with other organizations, calls must be issued well in advance -- at least six months, preferably longer; and that too frequent meetings in a given region will become a chore rather than a pleasure to attend.

The aim will be to keep the plan, and hence the meetings themselves flexible, but workable. Further details will be announced in due course.

The Thirtieth Annual Meeting will be held in Washington in 1949 on dates between April 20th and May 4, depending upon our ability to secure the necessary accomodations. The exact dates will be announced as soon as possible.

APPENDIX B--REPORT OF SPECIAL COMMITTEE FOR COOPERATION WITH INTERNATIONAL COMMISSION FOR STUDY OF TIDAL WAVES, APRIL 1948.

Martin A. Mason, Chairman

Clifford A. Barnes	Harry H. Hess	Walter H. Munk
Charles K. Green	Gabris H. Keulegan	Walter B. Zerbe
	Gordon A. Macdonald	

This Committee was intended to cooperate with the International Commission for the Study of Tidal Waves (Commission pour l'Etude des Raz de Marees) which was appointed orginally at the General Assembly of the International Union of Geodesy and Geophysics at Edinburgh, September 1936. The Commission was a joint body of the International Associations for Physical Oceanography, Meteorology, Seismology, and Vulcanology.

No report on the activities of the Commission was included in the minutes of the General Assembly of the International Union held in Washington, September 1939 and there is no record of the Commission having been re-appointed. Correspondence with the General Secretary of the International Union indicates that the Commission, in fact, no longer exists.

Under these circumstances the Special Committee has considered its position and the functions it might perform. Obviously since the International Commission does not exist, cooperation is not possible. It is, however, the opinion of the Special Committee that the Committee should be continued under a new directive and that it should be a joint committee of the Sections of Oceanography, Seismology, Meteorology, and Tectonophysics.

It is recommended therefore that the present Committee for Cooperation with the International Commission for Study of Tidal Waves be redesignated the Special Committee for Study of Tidal Waves and that it be directed to foster and encourage the study of tidal waves, through its own efforts and in cooperation with other national committees.

The Committee calls particular attention to certain, other than AGU, publications of unusual interest in the study of tidal waves. The United States Coast and Geodetic Survey has published charts of "Seismic Sea Wave Travel Times to Honolulu" enabling the computation of the time required for a seismic sea wave to reach Honolulu from an earthquake epicenter in the Pacific Ocean.

A list of seismic-sea waves compiled by N. H. Heck was published in the Bulletin of the Seismological Soceity of American, volume 37, October 1947. This list is a revision of a previous list, and includes a larger number of waves and more complete information than the earlier compilation.

Several papers treating the tsunami of April 1, 1946 have been published, of which the most extensive is a paper prepared by F. P. Shepard, G. A. MacDonald, and D. C. Cox. A paper titled "Travel Times of Seismic Sea Waves to Honolulu" by Bernard D. Zetler, appearing in Pacific Science, volume 1, July 1947 is of considerable interest in connection with the seismic sea wave travel time charts previously mentioned.

The Scripps Institution of Oceanography has been active in developing a tidal wave, or tsunami, recorder. The recorded data will permit further study of the characteristics of these long waves. The Coast and Geodetic Survey has been active in developing a detector of seismic sea waves, particularly for use in connection with proposed warning systems.

The United States Coast and Geodetic Survey is maintaining a file of tide-gage records which give evidence of the time of arrival of seismic sea waves.

APPENDIX C--REPORT OF THE SPECIAL COMMITTEE ON THE GEOPHYSICAL AND GEOLOGICAL STUDY OF THE CONTINENTS, 1947-1948

G. P. Woollard, Chairman

C. S. Beals
Francis Birch
Walter H. Bucher
Maurice Ewing
Roy W. Goranson
Ross Gunn
Sigmund I. Hammer
Harry H. Hess
Patrick M. Hurley
Henry R. Joesting
Ellis A. Johnson
Chester R. Longwell
J. B. Macelwane
H. A. Marmer
Frank Neumann
B. Perkins, Jr.
Roger R. Revelle
E. B. Roberts
D. C. Skeels
Nelson C. Steenland
William T. Thom, Jr.
J. Lamar Worzel

During the year ended April 1948, the Committee was active, as in the past, in furthering geophysical and geological studies related to the study of the continents. The Committee also participated in the Symposium of the Geological and Geophysical Study of New England held during the New England Meeting of the American Geophysical Union at Middletown, Connecticut, and

in cooperation with the Associate Committee on Geodesy and Geophysics of the Canadian National Research Council held a joint conference on the applications of geophysics to the study of continental structure at Ottawa during the meetings of the Geological Society of America.

The gravity meter on loan to the American Geophysical Union from the Humble Oil and Refining Company, was used during the year under the direction of the Chairman in making a regional reconaissance gravimetric survey of the Eastern Seaboard south of Washington, D. C. This was part of the general regional gravimetric program started several years ago under the auspices of the Committee which has been financed for the most part by grants in aid from the Penrose Fund of the Geological Society of America. The gravimetric measurements have been supplemented in most areas by measurements of the vertical component of the Earth's magnetic field and, in all, about 4000 stations have been established.

Through a cooperative arrangement with the Dominion Observatory of Canada, it is planned to tie the gravity and magnetic surveys of Canada and the United States together over the entire width of the Continent during the next two years as well as build up a nucleus of stations across the Continent which will permit gravitational and magnetic studies to be carried across the International Boundary and on and off the exposed pre-Cambrian shield area.

In the continuing study of the Continent by the United States Geological Survey, three gravitational traverses were established out to approximately half way across the continental shelf of the Gulf of Mexico in the vicinity of the Texas-Louisiana State Line. These observations were made with a gravimeter in a diving bell and stations were set at intervals of about two miles along each traverse. As a supplementary part to this program the same area has been magnetically mapped using the air-borne magnetometer. Additional magnetic investigations were made during the year in the Aleutians, Alaska, across the Atlantic Continental Shelf, in Bermuda, and over much of the State of Indiana.

As part of the geophysical program of the United States Coast and Geodetic Survey, a large scale study of the deflection of the vertical is now being made, using gravity data which embraces most of the Mid-Continent region of the United States and the Gulf Coastal Plain. This study has been made possible by contributions of gravity data from the various oil and exploration companies. Although most of these data have been released on a confidential basis, it is hoped that they will be available at a later date for other purposes. As part of the above program, the United States Coast and Geodetic Survey and the United States Geological Survey are also making a cooperative gravimetric survey of eastern Kansas and Oklahoma and northern Arkansas. These measurements are being made with a gravimeter and supplemented with pendulum observations.

The United States Coast and Geodetic Survey plans to continue the pendulum-observation program, and hopes eventually to develop a network of stations with a hundred-mile spacing covering the country. It is also planned to secure a gravimeter for carrying out detailed investigations in local areas.

Maurice Ewing and J. Lamar Worzel and their associates at Columbia University completed during this past year a series of gravitational traverses across the Atlantic Continental Shelf between Nova Scotia and Cape Hatteras, a series of traverses off the West Coast of South America between Panama and Valparaiso, Chile, a series of observations off the North Coast of South America between Panama and Trinidad, and several traverses in and around the Bahama Banks. This work was done with Vening Meinesz pendulums on loan from the Woods Hole Oceanographic Institution in U. S. Navy submarines, and was financed by a grant from the Geological Society of America and as a project of the Office of Naval Research. Future plans include additional traverses across the Atlantic Continental Shelf south of Cape Hatteras and considerable work in the Pacific Ocean including a study of the Aleutian Trench.

Other work planned by the group at Columbia University includes resumption of the seismic depth studies across the Atlantic Continental Shelf, and several traverses are planned for this summer south of Cape Hatteras. As a supplement to the offshore traverses in South America, it is also planned to make a couple of gravimetric traverses across South America using a gravimeter and pendulum apparatus.

In Canada through the Associate Committee for Geodesy and Geophysics of the Canadian National Research Council an extensive gravimetric, magnetic, seismic, radioactive, and thermal measurement program is being made in conjunction with a detailed geologic program for a portion of the shield area in which there is considerable geologic information. The latter program includes the intensive study of air photographs for indications of geologic structure and the compilation of detailed geologic maps.

In addition, the Dominion Observatory in cooperation with the Department of Mines is active in extending the gravimetric and magnetic mapping of the country, using gravimeters and vertical component magnetic variometers. A large part of this work is in formerly inaccessible parts of the country and is being accomplished by taking the instruments into the numerous lakes of the "back country" by plane and making observations at these locations.

The seismic program, using large explosive shots for studying the structure of the Appalachian Mountains, that is being conducted by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington is now in active operation, and it only appears to be only a matter of time until this investigation will furnish some definite information as to the nature of the crustal deformation underlying this Mountain Range.

At the Massachusetts Institute of Technology, it is planned to start a program this year on the radioactive age determination of the rocks in the pre-Cambrian areas to see if they can be dated and possibly correlated with rocks of similar age in other parts of the world. This program beside dating the rocks involved will also yield information concerning the apparent acceleration in periods of orogeny.

In conclusion, attention should be called to the role of the Office of Naval Research in furthering fundamental research. For the first time relatively large sums of money are available for pure research and many projects higherto considered impossible because of their financial demands can be seriously considered. This will in no way minimize the importance of the grants in aid from the Geological Society of America and the cooperation extended by the various other goverament agencies in furthering scientific investigations, but it will certainly be an important factor in determining the direction in which basic research on continental structure will take during the next few years.

APPENDIX D--REPORT OF THE SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS FOR THE YEAR 1947-1948

Harlan T. Stetson, Chairman

C. F. Brooks
J. H. Dellinger
J. A. Fleming
S. A. Korff
D. H. Menzel
G. W. Pickard
J. Q. Stewart
W. T. Thom, Jr.

The year 1947 to 1948 has probably seen the passing of the present peak in sunspot numbers occurring very closely with Waldmeier's prediction of 1947.6.

J. H. Dellinger of our Committee, in charge of the Central Radio Propagation Laboratory, has actively enlarged the program to contribute materially to the whole field of Cosmic-Terrestrial Relationships. Following the investigations of J. Q. Stewart, this Bureau has done much in furthering the prediction of sunspot numbers by attempting to make allowance for the regression toward the mean cycle by a somewhat more elaborate method.

Dellinger has kindly summarized the work carried on under his direction as follows: "The very high sunspot numbers which have been observed during the recent months have created some concern regarding the consistency of the Zurich sunspot data since there has been a change of observers recently. It is hoped that the use of sunspot numbers observed by American Observatories including volunteers may result in a more reliable and consistent sunspot number, as free as possible of variable reduction factors.

"The Model C_2 ionosphere recorder was shipped by air to Bocaiuva, Brazil, with the National Geographic Eclipse Expedition for the purpose of obtaining information on the behavior of the ionosphere during the total eclipse of May 20, 1947. From this type of information, it is possible to deduce facts about such things as the manner in which radiation from the Sun produces the ionized layers and the manner in which ionization decays when the Sun's ionizing effect is removed. James Watts and Franklin Kral, who had been instrumental in the design and construction of the Model C_2, erected and operated this equipment at Bocaiuva. They returned from Brazil with excellent records. In all, some 15,000 records were taken over a period of one month and five days, ordinarily at 15-minute intervals. During test periods and from 00^h00^m to 16^h00^m local time on the day of the eclipse, records were made every five seconds both on the regular camera and on a 16-mm motion-picture camera. The records taken during the eclipse are still to be analyzed and editing of the motion pictures has just begun. Qualitatively, however, the records show the formation of a full-fleged F_1-layer, with a sharp critical frequency from a vestigial type without

a definite critical frequency. This F_1 critical frequency moved down to a very low value at a high rate of speed during the eclipse and then gradually increased in value, merging with the F_2 after several hours. A well defined F_1-layer is not ordinarily visible in the latitude of Bocaiuva.

"A new service was inaugurated, consisting of warnings of the likelihood of occurrence of sudden ionosphere disturbances (SID). The frequency with which these disturbances are occuring at the present time, approximately 100 on paths terminating at Washington during the first eight months of 1947, has made them of great concern to communication circuits. SID have heretofore been regarded as virtually unpredictable, but some relationships, revealed by examination of data collected during the last sunspot cycle, indicated the possibility of forecasting them to a certain extent. The prediction consists of designating days on which SID may be expected to occur and the probability of occurrence; it is expected that during times of fairly high solar activity the efficiency of the prediction will be about 50 per cent; that is, when it is stated an SID wil occur on a day, an SID will occur in 50 per cent of the cases, while 50 per cent of the days during which SID do occur will not be predicted.

"Permanent equipment was put in service to carry on the study of meteors. One meteor detecting equipment was set up on 27.2 Mc and another at 13.6 Mc. The transmitting equipment consisted of two modified marine-type communications transmitters to give five-kw peak pulse output. The receivers were standard communications-type receivers modified for pulse reception. The most successful results were obtained on the Geminid shower on December 10, 11, and 12, 1947 and on random meteors on December 19, 1947. The dependence of reflection from meteor trails on the relationship between the plane of polarization of the radio waves and the direction of the meteoric radiant, indicated by observations on the Geminid shower last year, was not confirmed by the recent more careful observations. The effects previously noted were probably due to the directional pattern of the antennas. A marked dependence on the distances from which reflections were returned and the altitude of the radiant was observed. This is adduced as evidence that the reflections are most strongly returned when the ray path of the radio waves is perpendicular to the meteor trail. Most observations were conducted on a frequency of 27.2 Mc. Comparison was made between the frequency of reflections on 13.6 Mc and on 27.2 Mc. It appeared that many more reflections were obtainable with the lower frequency but owing to interference and improper control on power emitted, it was not yet possible to derive an exact expression for relating the efficieny of the two frequencies in detecting meteors.

"Examination of the F_2 critical frequencies at Huancayo has shown pronounced lunar effects. The investigation of these was undertaken in an attempt to explain the general geomagnetic control of the upper ionosphere as called for by a theory previously proposed. The theory anticipates these lunar variations as a result of electric forces caused by the lunar variations in geomagnetism which gives rise to electric fields crossed with permanent magnetic field of the Earth. Quantitatively these forces are of the correct order of magnitude. The explanation is further supported by corresponding seasonal variations in both the geomagnetic and ionospheric phenomena. A simple tidal influence on the ionosphere does not appear adequate to account for these effects because of phase relationships involved. The variation in F_2 critical frequency with phase of the Moon is most pronouced in the noon values which, from November to February, average 1.7 Mc higher three or four days after the quarters of the Moon than after the new and full Moon.

"Because of the increase in ion density throughout the ionosphere and particularly in the F_2-layer with increasing sunspot number, it has been assumed that maximum usable frequencies shown will correspondingly increase. However, studies of changes in maximum usable frequency have shown that at some hours of the day and at certain locations, particularly during the evening hours in equatorial regions, no appreciable increase in maximum usable frequency occurs from sunspot minimum to sunspot maximum. A detailed examination of the Huancayo ionospheric records, which were made to study this effect, showed that the increase in ion density responsible for the reflection of the highest usable frequency is compensated by the increasing obliquity with which the ray propagated over the long distances impinges on the ionosphere. Under such conditions, the distances over which a wave may be propagated by a single reflection may exceed the 4000-km limit commonly assumed for single-hop propagation.

"Work was completed on the installation of the originally contemplated four cosmic-noise recorders on 25, 50, 75, and 110 Mc and continuous automatic recording begun. A means was thus afforded for obtaining the intensity and frequency law of cosmic noise in this range which would provide a knowledge of the limitations which the phenomenon imposes upon services utilizing these frequencies."

Donald H. Menzel, who has been added to our Committee, emphasizes that one of the greatest needs in the study of Cosmic-Terrestrial Relationships is improved information concerning solar activity. A major portion of his time as Associate Director and Director of Solar Research at the Harvard Observatory has been given to improving equipment and observing techniques with the view of obtaining better information about solar activity and its effect upon the Earth.

Through funds supplied by the Office of Naval Research, Menzel has been able to design new and better equipment and progress has been made in the construction of new coronagraphs, one of which will be of 16-inch aperture. There are under design special filters and that will make possible the obtaining of records of activity on the disk that should be particularly useful for the study of certain types of cosmic-relationships such as magnetic disturbances and solar noise. Special studies of the rotation of the corona have been carried on at the High Altitude Observatory at Climax, Colorado, and investigations undertaken concerning the relationship of the bright coronal areas to recognizable solar features such as faculae and calcium flocculi. Menzel believes a close correspondence exists between bright areas, especially the green line, with the floccular patches. He has been able already to show that the corona tends to rotate with the Sun, that the bright coronal areas are semi-permanent, and are possibly related to the mysterious M-regions of the Sun.

A new classification of prominences is in progress. Because of the considerable importance in the field of solar-terrestrial relationships of the variation of the ozone content of the upper atmosphere, plans are in progress for the observation of the quantity of ozone.

The Harvard Observatory, in cooperation with the Observatory of the University of Michigan, is undertaking the study of the far ultraviolet of the solar spectrum, in connection with the V-2 rocket observations made at the Naval Research Laboratory.

Menzel's new theory of absorption lines in the solar spectrum affords the possibility of application to actual observations, the results of which have disclosed useful information concerning physical conditions in the Sun's upper atmosphere.

Additional studies, both theoretical and observational, reported by Menzel, relate to a solar mechanism for the production of cosmic rays, a preliminary report of which has already appeared in a letter to the Editor of Nature. Menzel postulates that variations in local magnetic fields of the Sun may be large enough to cause long wave radio waves, with periods of the order of from one to perhaps 100 cycles per sec. It is of interest to note that waves of the type postulated might account for the luminosity of the night sky as a sort of electrodeless discharge. In addition, Menzel has progressed in his theory of the ionosphere, based on an assumption concerning a polytropic atmosphere with various types of mechanisms for the formation of ionized layers. It is expected that this study will be published within a few months.

Charles F. Brooks, Director of the Blue Hill Meteorological Observatory, reports that continuous records of total insolation on a horizontal surface, of diffuse insolation on a horizontal surface, of total insolation on a vertical surface facing south and of the intensity of the solar beam at normal incidence were maintained cooperatively by the United States Weather Bureau and Blue Hill Observatory throughout the past 12 months. The records of total on a horizontal surface and of the beam at normal incidence are now in their 16th year; that of total facing south in the fourth year, and that of diffuse in the third year. Routine observations of aurora continue (64th year).

The interest in the cause of the very snowy winter just passed led to a small investigation of the relation of snowy winters to sunspots. They were found to occur with both low and high sunspot numbers, but with the average of sunspottedness slightly higher than normal on the occasion of snowy winters. The excess was not sufficient to be statistically significant for the small sample used.

Serge A. Korff of New York University with L. Greenberg and L. G. Collyer flew to Puerto Rico on January 16, 1948 for the purpose of making cosmic-ray observations as part of a long-range program designed to determine variation of the intensity of cosmic rays in various parts of the world. This program included the charting of cosmic-ray strength with respect to altitudes up to 20 miles and use of rubber balloons, five feet in diameter, to carry aloft a number of instruments for making the desired measurements. In addition, observations were also made in Colorado during the summer of 1947 and it is expected will be continued in the summer of 1948.

Jno. A. Fleming, who has retired as Director of the Department of Terrestrial Magnetism, CIW, has called attention to the several publications of that Institution, especially the report of the new

Director, Merle A. Tuve, and Publication 175, volumes 7, 8, 10, 11, 12, and 13 in which are contained researches of terrestrial magnetism relative to magnetic and ionospheric results from Watheroo, Huancayo, College Alaska, and other stations.

At the Cosmic-Terrestrial Research Laboratory in Needham, the radio field-intensity program has been carried on systematically, and hourly data reduced and analyzed and forwarded to the CRPL in Washington. Under a contract with the Massachusetts Institute of Technology and the Office of Naval Research investigations have been furthered which would not have otherwise been possible.

A study of continuous field recordings of WWV at Needham, Massachusetts, 373 miles from the transmitter at Beltsville, Maryland, has revealed that the diurnal pattern of reception undergoes a progressive metamorphosis, not only with the seasons, but with the change in sunspot numbers. This suggests the possibility of predicting fields over a given path based on actual records of performance, provided the records obtained at Needham are representative of a considerable area throughout which such variations may take place.

A temporary field station for recording field intensities of WWV, operated during the summer of 1947 at Intervale, New Hampshire, at a distance of 463 miles from Beltsville, has made possible direct comparison with fields obtained at the Cosmic-Terrestrial Research Laboratory at Needham over the same interval. Results show the same general form of diurnal variation at the two stations for both the five Mc and the ten Mc frequencies. The logarithm of the ratio of the five Mc fields Needham/Intervale ranges from 1.3 at night to 1.7 during the noon hour.

Subsequently, a mobile recorder was set up at New Haven, Connecticut, at a distance of 270 miles from Beltsville, and simultaneous recordings were made during the autumn of 1947 with similar results. Sudden ionospheric disturbances and major fadeouts have been observed to occur simultaneously at Intervale and Needham, and at New Haven and Needham. The results of these investigations indicate that the changing patterns observed at Needham must essentially apply to a considerable area approximating at least a 100-mile radius from the Laboratory at Needham. A study of simultaneous observations of field intensities at Needham, at Intervale, and New Haven has been published in the March 1948 number of Terrestrial Magnetism and Atmospheric Electricity.

More recently, an auxiliary field station has been set up at Tuckahoe, New York, in Westchester County for further comparison of field intensities at a point 50 miles nearer the WWV five Mc transmitter than is New Haven.

G. W. Pickard has continued his study of tropospheric transmission, utilizing data collected at the Needham Laboratory relative to reception of W2XMN 44.1 Mc and W2XEA 92.1 Mc from Alpine, New Jersey. A detailed study of the variations in reception at the lower frequency with atmospheric refraction appeared in the Proceedings of the Institute of Radio Engineers in Decmeber 1947. Since this paper was presented sufficient data have been collected relative to the high frequency, 92.1 Mc, for a study of comparative reception. In tropospheric transmission there may be considered three general modes of propagation: First, a general bending by a more or less uniform lapse rate in the lower half of the troposphere; second, by a reflection at grazing incidence angle from sharp changes in refractive index, such as occur at temperature and humidity inversion levels; and third, by wave ducts which trap and convey a part of the radiation from transmitter to receiver.

The United States Weather Bureau has been most cooperative in furnishing upper atmospheric observations from their RAOB studies.

It seems probable, on what appear to be reasonable assumptions, that W2XMN fields at Needham are largely controlled by refractive lapse rate in the first few kilometers of the lower troposphere, with secondary contributions by reflection from low inversions. It seems unlikely that duct transmission plays any significant part. As regards the higher frequency of W2XEA, 92.1 Mc it seems equally probable that the principal controls for transmission are changes in lapse rate in the first few kilometers and reflection from low inversions.

A comparison of reception of these two frequencies is on the program for presentation at the Washington Joint Meeting of the American Section, International Scientific Radio Union, and the Institute of Radio Engineers, on May 3.

The refraction of tropospheric radio waves involves a seasonal variation that yields higher refractive values in summer and lower in winter. Since this is contrary to the usual refraction variation entailed in astronomical observations, involving star position, your Committee has had the able services of W. D. Lambert of the United States Coast and Geodetic Survey who, with members of our Committee, has reinvestigated certain phases of atmospheric refraction.

It appears that an important change in refraction coefficient occurs in the spectrum between frequencies of light waves and radio waves of very high frequencies which is dependent upon the relaxation time of polar molecules so that the effect of water vapor upon wave lengths of the order of one cm is very different than that upon waves of the order of the visible spectrum wave length.

Considerable progress has been made on the reduction of over 20 years of records of WBBM at broadcast frequency. It now appears that practically all of this material can be reduced to field values and this in time can be equated to an adopted power.

A continued study of night and day field-intensities at the Cosmic-Terrestrial Research Laboratory have shown that night fields of WWV, five Mc have increased consistently with a sunspot number of 20 to a sunspot number of 110, but with higher solar activity than this a decline has been evident. Day fields have declined steadily with the increasing of sunspot numbers during the present cycle from 20 to values of 150. Broadcast frequencies from WBBM, Chicago, with few exceptions have declined steadily with the increase of sunspot numbers throughout the present solar cycle. With a decrease in value of sunspots anticipated in the next few years these night fields at broadcast frequencies may be expected to increase again. In the case of WWV, ten M_c both day- and night fields have shown increases with sunspot numbers since the beginning of the records in 1945.

The data on WWV, 15 Mc is rapidly accumulating and soon will be of sufficient quantity to begin analyses of the propagation on these shorter waves over this path.

The Chairman of your Committee, with the cooperation of other members, has been able to supply the Government with valuable data applicable to the evaluation of certain bills before Congress concerning wave-length allocations.

It is gratifying to note the increase in the interest of all phases of Cosmic-Terrestrial Relationships not only for their geophysical implications but for the many important applications to the communication industry, in which also Government agencies, and the National Defense are concerned.

APPENDIX E--MINUTES OF THE ANNUAL MEETING OF 1948, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The Twenty-Ninth Annual Meeting of the Section of Geodesy was called to order by President H. W. Hemple, at 09^h03^m, April 23, 1948, in Conference Room B, Interdepartmental Auditorium, Washington, D. C. About 100 members and guests were in attendance.

The minutes of the Twenty-Eighth Annual Meeting were declared approved as published in the June 1947 Transactions with the following correction: At the end of the second paragraph change "August 1947" to read "August 1946."

J. B. Small, the Section's Membership Committeeman, reported that the American Geophysical Union had its greatest increase in membership in its history during the past year. Approximately 1500 new members had been added, making the total membership approximately 4300.

N. F. Braaten, Editor for the Section of Geodesy, reported that additional contributions to the Transactions are solicited as there was only a small backlog of papers awaiting publication. He asked for more written comments on published articles, and for criticism of the Transactions and suggestions for improvements in them.

H. S. Rappleye submitted for the Resolutions Committee three resolutions which were recommended by the Section to be adopted by the Union.

W. D. Lambert offered the following statement relative to forthcoming international meetings: "Before taking up the General Assembly in Oslo of the International Union of Geodesy and Geophysics, I should like to mention another international meeting that just precedes it, the General Assembly of the International Astronomical Union at Zurich, Switzerland.

"Geodesy and Astronomy (as distinguished from Astrophysics) have much in common. The flattening of the Earth can be derived by more than one astronomical method. The preferred value of one important astronomical constant, the parallax of the Moon, is determined, not by direct astronomical observation but by mathematical inference from two observed quantities; (among others) from the absolute value of gravity (which is the physicist's job), and from the radius of the Earth (which is our job). The value of the parallax so deduced is preferred to that determined by direct observation, because of the unknown deflections of the vertical and the unknown elevations of geoid above spheroid at the observatories at the two ends of the line that serves as the base of the triangle that determines the parallax. The usual vertices of this triangle are: Moon, Greenwich, Cape of Good Hope. It will be our job to do away with these uncertainties.

"The ties between Astronomy and Geodesy correspond in our scientific set-up to three joint committees of the Astronomical Union and of the Association of Geodesy. There are committees for the Variation of Latitude, Time, and Longitude. Some members of these committees are named by astronomers, some by geodesists.

"In the past the International Astronomical Union and the Association of Geodesy have met in different years and these Joint Committees have met in what have been considered as full-dress sessions in connection with the General Assemblies of both organizations, though at one time the attendance might be predominantly of astronomers, at another of geodesists.

"This time the two organizations meet in the same year and at nearly the same time and it seemed inadvisable to hold full-dress sessions twice within a month. Accordingly,the important meetings will be held at Zurich in connection with the meeting of the International Astronomical Union. The meetings of the Committees at Oslo will be mainly for information and to allow those to be heard who could not be present at Zurich.

"Accordingly, I hope that all those who are interested in the work of these three Joint Committees, Variation of Latitude, Time, and Longitude, and are able to go to Zurich will plan to do so. If they will give me their names, I feel sure I can arrange for the minor detail of credentials, and similar matters.

"Commenting now on the General Assembly at Oslo, the Associationof Geodesy is a branch of the larger or parent organization, the International Union of Geodesy and Geophysics. The meetings of the governing bodies of Association and Union will hold a series of business meetings on August 17 and 18.

"On August 19 the general meetings of the Union and Association will begin. In the past, much of the work of the Association of Geodesy was done in committee. There was a distractingly great number of committees. Many delegates found that in order to attend all the committee meetings that interested them they would have had to be in several places at the same time. To remedy this inconvenience it was decided at Paris in 1946 to organize the work in five principal sections: Triangulation, leveling, geodetic astronomy, gravimetry, and figure of the Earth (geoid), each with a chairman, who is ex officio a member of the Executive Committee. If a section so desires, it can assign parts of its work to committees or sub-sections, but it is to be hoped that the creation of these special committees or sub-sections will not be carried so far as to bring back the old nuisance of multitudinous and clashing committee meetings.

"I have the tentative program and day-by-day time table for the work of the two governing bodies of the Association, namely, the Executive Committee and the Council (or Permanent Commission), of the five sections already mentioned, and of three committees whose work cuts across section lines. It was prepared by the General Secretary. It should be clearly understood that it is all entirely tentative and subject to such modification as may seem desirable.

"A word or two about the governing bodies of the Association and about matters of business to come before the Oslo meeting. There is an Executive Committee, which is much like other Executive Committees. There is also the Council or Permanent Commission, an inheritance from the old Pre-World-War-I International Geodetic Association, the Internationale Erdmessung. The convenience of such a body has become so evident that the parent organization, the International Union of Geodesy and Geophysics, has recently seen fit to establish a council of its own. The Permanent Commission of the Association of Geodesy is composed of one member from each adhering country. That member is the normal channel for official communications between the Central Office and the officers of the Association of Geodesy on the one hand and the geodetic institutions and individual geodesists of the country concerned on the other.

"The Permanent Commission is consulted by correspondence on matters deemed too important to be settled by the Executive Committee, particularly on financial matters. In the General Assembly the voting on scientific questions is by individuals, each person having one vote. But for administrative and financial questions the voting is by countries, with each country having sometimes one vote, sometimes several, with the larger countries having more votes. On such questions the decision of the Permanent Commission will foreshadow the decision of the Assembly, since the same individuals do the voting in both bodies.

"Up to the present I have been the ex officio American member of this Permanent Commission, but under the new by-laws there will be no ex officio members of the Permanent Commission and in any case I shall soon retire from office. The Section of Geodesy of AGU should therefore designate the American member of the Permanent Commission. He will serve during the pleasure of the Section.

"Two matters of business will come before the General Assembly. First, the discussion and possible adoption of new by-laws. A draft has been prepared by the General Secretary. It is available for examination and criticism. The draft embodies the decisions of our Paris meeting of 1946; it also formalizes some of the things that we have done and are doing but which hitherto have not been embodied in any general rule. Then there will be the election of officers for such terms as the adopted by-laws may provide.

"A final word about scientific communications. They will be given, in general, at the section meetings. If you have something to say, write it and have mimeographed copies made, 100, 150 or so, so that they can be distributed at Oslo. Remember the difficulties of addressing a polyglot scientific gathering. No one language will get your meaning across to everyone there. If you have no means of doing the mimeographing or other duplicating, or to pay for it, send your manuscript to the Paris Office of the Association and the necessary number of copies will be provided."

Walter D. Lambert was unanimously elected as American member of the Permanent Commission.

The Business Meeting of the Section was adjourned and the following scientific papers were presented:

(1) Donald A. Rice: Gravimetric deflections by the method of condensation (discussed by H. W. Hemple and C. H. Swick)
(2) F. R. Gossett: Flare triangulation (discussed by B. K. Meade, W. D. Lambert, C. A. Whitten, C. D. Meaney, J. L. Speert, F. W. Hough, M. E. Compton, and P. D. Thomas)
(3) C. W. Kroll: A rigorous method for computing geodetic distance from shoran observations (discussed by Lyman J. Briggs and D. A. Rice)
(4) Floyd W. Hough: Progress of the European triangulation adjustment (discussed by C. L. Garner)
(5) C. A. Whitten: Horizontal Earth movement, vicinity of San Francisco
(6) J. L. Worzel and Maurice Ewing: Gravity measurements at sea, 1947 (read by J. L. Worzel)
(7) C. H. Ney: The loop closure of the Gulf of St. Lawrence triangulation nets (read by W. D. Sutcliffe in the absence of Mr. Ney)
(8) J. H. Brittain: Progress in geodetic surveys by the U. S. Coast and Geodetic Survey since July 1947
(9) Manuel Medina: Geodetic work accomplished in Mexico for April 1947 to May 1948 (this paper was read by title)
(10) G. P. Woollard: Recent gravity surveys

The meeting adjourned at 12^h25^m.

FRANK L. CULLEY, Secretary

APPENDIX F--MINUTES OF THE ANNUAL MEETING OF 1948, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Ninth Annual Meeting of the Section of Seismology was called to order by President Frank Neumann at 09^h15^m, April 23, 1948 in the Auditorium of the National Academy of Sciences, National Research Council Building, Washington, D. C.

The minutes of the Twenty-Eighth Annual Meeting were approved as published in the Transactions [v. 28, pp. 506-507, 1947].

M. A. Tuve, Perry Byerly, and L. M. Murphy were asked to serve as the Committee on Resolutions and to report back to the Section following the intermission period in the scientific portion of the program which followed.

As an item of new business, Richard M. Field asked if the Section of Seismology of the American Geophysical Union desired to make any recommendations to the Association of Seismology of the International Union of Geodesy and Geophysics, particularly as regards the study of continental structure. In the discussion which followed attention was called to the need of a closely spaced network of seismological observatories to obtain the data necessary for studies of continental structure by seismic methods. Beno Gutenberg pointed out that as yet no complete report had been made as to which and how many of the pre-war stations had been re-established and that the delegation to Oslo would make recommendations after this information was obtained. Field asked Gutenberg if he would so state the situation at the Oslo meeting. In view of these circumstances, it was agreed that no formal action by the Section was required.

Since there was no further business, the Section proceeded to the scientific portion of the program as follows:

(1) J. E. Ramirez; A preliminary report on research on short period microseisms by J. B. Macelwane; F. Robertson; J. E. Ramirez; J. Volk; C. Kisslinger; and W. F. Sprengnether, Jr. at St. Louis University on contract with the Office of Naval Research)
(2) M. A. Tuve; R. W. Goranson; J. W. Greig; W. J. Rooney; J. B. Doak; and J. L. England: Progress report on local seismic shots
(3) Beno Gutenberg and Charles F. Richter: Earthquake study in Southern California, 1947

Following the discussion of this paper, there was a brief intermission. After the intermission, the Committee on Resolutions made the following recommendations: That the American Geophysical Union (1) Express our thanks to the Finn Ronne Expedition for the establishment of the Seismic Station in the Antarctic and to recommend the continuance of this station; (2) thank the United States Bureau of Standards and the United States Navy for furnishing Time Signal Service for our use; and (3) request that, if possible, Standard Time Control be furnished at the Naval Microseismic Stations. A motion was made and carried instructing the Secretary to transmit these resolutions to Earl Ingerson, Chairman of the Committee on Resolutions of the American Geophysical Union.

The remainder of the program was given to the scientific papers as follows:

(4) E. B. Roberts: Some recent seismological activities of the U. S. Coast and Geodetic Survey
(5) James B. Macelwane: Progress report of the Jesuit Seismological Association
(6) H. E. McComb: A two-component shock recorder
(7) D. S. Carder: Seismic evidence of a first order discontinuity at 160 km
(8) L. M. Murphy: A confirmation of regional travel times for earthquakes at Santiago, Chile

The meeting adjourned at 12^h25^m.

FLORENCE ROBERTSON, Secretary

APPENDIX G--MINUTES OF THE ANNUAL MEETING OF 1948, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Ninth Annual Meeting of the Section of Meteorology was held April 22 and 23, 1948, in the Auditorium of the Natural History Building of the National Museum, Washington, D. C. More than 300 members and guests attended the several sessions.

The opening session was held from 09^h20^m to 12^h30^m, April 22, 1948, with President Horace R. Byers presiding. Since no corrections were received, the President declared the minutes of the Twenty-Eighth Annual Meeting of the Section of Meteorology approved as published in the Transactions [v. 28, p. 507, June 1947]. The President then appointed the Committee on Resolutions (B. C. Haynes, Chairman; Commander G. Van A. Graves, L. P. Harrison).

The second session, meeting from 14^h00^m to 17^h00^m on April 22, was held jointly with the American Meteorological Society and consisted of a Symposium on Tropical Meteorology under the Chairmanship of Harry Wexler.

The third session, held from 09h00m to 12h00m on April 23, was a Symposium on Long Range Weather Problems under the Chairmanship of Bernhard Haurwitz. The assembled Section considered a resolution submitted by Daniel T. O'Connell, City College of New York and which was concerned with G. I. benefits for Weather Bureau employees who served with the United States Coast Guard during the War. The Section expressed itself as in fullest sympathy with the thoughts expressed in O'Connell's communication, but did not accept the resolution on the grounds that the proposed action was not a proper function of the Meteorology Section or the American Geophysical Union.

The scientific program for the three sessions consisted of the following papers:

First session, Thursday morning, April 22, 09h00m, Horace R. Byers, Chairman

(1) J. Ross Heverly: Similitude of artificial and natural fogs
(2) J. Ross Heverly: Super cooling and crystallization
(3) Charles L. Hosler: The use of pryheliometer records in objective weather forecasting
(4) Charles L. Hosler: An application of weather forecasting to safety in coal mines
(5) Hans Neuberger: A simple method for shallow meteorological soundings
(6) John R. Gerhardt: Microtemperature fluctuations
(7) P. O. Huss and D. J. Portman: Micrometeorological station for study of natural wind and atmospheric diffusion
(8) August Raspet: The sailplane as a meteorological probe
(9) W. A. Baum: On the probem of super auto-convective lapse rates in the micro-climatic layer

Second session, Thursday afternoon, April 22, 14h00m, Harry Wexler, Chairman, Symposium on Tropical Meteorology, held jointly with the American Meteorological Society.

(10) Herbert Riehl: The typhoon formation, September 11-13, 1945
(11) Lester Hubert: High troposphere westerlies over the Equatorial West Pacific Ocean
(12) R. H. Simpson: Meteorological notes on high-level reconnaissance into the hurricane of September 1947
(13) Samuel B. Solot: Variations of Hawaiian precipitation patterns
(14) W. H. Haggard: On the distribution of precipitation in the Hawaiian Islands
(15) D. A. Rodgers: Air Weather Service Sferic Operations in the Caribbean
(16) W. J. Kotsch: Investigation of the slice method for forecasting atmospheric stability and instability in tropical latitudes

Third session, Friday morning, April 23, 09h00m, Bernhard Haurwitz, Chairman, Symposium on Long Range Weather Problems

(17) H. C. Willett: Patterns of world weather changes
(18) G. W. Brier: Changes in the Northern Hemisphere sea level circulation in the 40-year period 1899-1939
(19) J. Namias: Evolution of monthly mean atmospheric circulation and weather patterns
(20) R. D. Elliott: Blocking action, an initial phase in a long period weather process
(21) I. P. Krick: The use of circulation classes in long range weather forecasting
(22) S. B. Solot: Relationships between large scale atmospheric flow patterns and Hawaiian precipitation

WOODROW C. JACOBS, Secretary

APPENDIX H--MINUTES OF THE ANNUAL MEETING OF 1948, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNTION

The Twenty-Ninth Annual Meeting of the Section of Terrestrial Magnetism and Electricity of the American Geophysical Union was called to order at 14h10m on Wednesday, April 21, 1948, in Conference Room B of the Interdepartmental Auditorium, with President Roman presiding. There were about 150 members and guests in attendance. The minutes of the previous meeting, as published in the Transactions for June 1947, were approved with one correction, namely, the word "classified" should be changed to "clarified" [p. 509, line 2]. After routine announcements, the remainder of the session was devoted to the following scientific program:

(1) S. E. Forbush: Solar influences on cosmic radiation
(2) A. H. Shapley and J. V. Lincoln: Some methods for general prediction of sudden ionospheric disturbance

(3) A. G. McNish and T. N. Gautier: Lunar effects on the ionosphere
(4) C. W. Gartlein: Aurora spectra showing broad hydrogen lines
(5) J. Kaplan: Dissociative recombination in the upper atmosphere (by title)
(6) W. D. Parkinson: Atmospheric ionization during thunderstorms at Huancayo, Peru
(7) O. H. Gish and G. R. Wait: Electrical surveys over thunderheads (by title)

There was informal discussion from the floor following several of the papers, particularly Nos. 2, 3, and 4. The first session was concluded at 16^h15^m.

The second session was convened in the same room at 14^h08^m on Thursday, April 22, 1948. At this session the following papers were presented:

(8) L. R. Alldredge: Preliminary report on the magnetic total field intensity anomalies between Adak, Alaska, and Kwajalein, Marshall Islands
(9) W. E. Wiles: Report on a modified wild-pattern Earth-inductor inclinometer
(10) R. F. White: Characteristics of some alloy magnet for geomagnetic instruments
(11) J. B. Macelwane and William F. Sprengnether, Jr.: The Sprengnether-Macelwane magnetometer
(12) V. F. Hess and J. Donald Roll: The indentification of the surplus gamma radiation from granite
(13) Elliott B. Roberts: Current magnetic work of the United States Coast and Geodetic Survey

At the conclusion of the scheduled program, the group was favored with a brief informal talk by Andrew Thompson concerning his experiences with the recently-concluded Antarctic expedition headed by Finn Ronne. There was also some discussion led by R. M. Field concerning the problem of mapping, particularly over the great ocean areas, the "background" magnetic field with local anomalies suppressed in some way, perhaps through use of airborne equipment. The international aspects of the problem were mentioned, and it was voted to designate a Committee to investigate the feasibility of a recommendation to the Executive Committee of the Union for an international cooperative project along these lines. The meeting was adjourned at 16^h00^m.

DAVID G. KNAPP, Secretary

APPENDIX I--MINUTES OF THE ANNUAL MEETING OF 1948, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Twenty-Ninth Annual Meeting of the Section of Oceanography was held April 21, 1948, in Conference Room B, Interdepartmental Auditorium, Washington, D. C. The session convened at 09^h30^m and adjourned at 12^h45^m. As both the President and Vice-President of the Section were not present, L. O. Colbert presided at the request of the Secretary.

The minutes of the previous Annual Meeting were published in the Transactions [v. 28, p. 509, June 1947], and as no corrections or additions were received, the Chairman declared them approved as printed.

The scientific program consisted of the presentation and discussion of the following papers:

(1) Leo O. Colbert: Oceanographic activities of the U. S. Coast and Geodetic Survey
(2) J. F. Farley: Coast Guard activities in oceanographic work and plans for the future
(3) C. O'D. Iselin: Research in oceanography at the Woods Hole Oceanographic Institution during April 1947 to April 1948
(4) Martin Mason: Oceanographic activities of the Corps of Engineers
(5) C. A. Burmister: Electronic control for offshore surveys
(6) H. R. Seiwell: Oceanographic factors in the determination of underwater depths from aerial photographs
(7) C. C. Bates: Utilization of tabulated sea and swell data
(8) L. P. Allen and R. H. Fleming: A process involved in the disintegration of sea ice

The following papers were read by title:

(9) W. B. Zerbe: The tide in the David Taylor Model Basin
(10) Lewis F. Richardson and Henry Stommel: Note on eddy diffusion in the sea

Attendance at the session was approximately 100.

R. H. FLEMING, Secretary

APPENDIX J--MINUTES OF THE ANNUAL MEETING OF 1948, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Volcanology of the American Geophysical Union was held on April 21, 1948, in the Auditorium, Natural History Building of the National Museum, Washington, D. C. The meeting was called to order by Clarence S. Ross at 09^h30^m, in the absence of the President and Vice-President of the Section.

The minutes of the previous Annual Meeting had been published in the Transactions [v. 28, pp. 510-511, June 1947], and as no corrections were received they were approved. There was no other business.

The morning session, comprising seven scientific papers, was as follows:

(1) P. D. Krynine, R. L. Folk, and J. C. Griffiths: A new mica periodotite occurrence from a a deep well in New York State (presented by R. L. Folk)
(2) Preston E. Hotz: Structure of some diabase sheets in southeastern Pennsylvania
(3) Esper S. Larsen, Jr.: The relation between Earth movements and volcanism in the San Juan Mountains of Colorado
(4) E. F. Osborn: Cellular structure in glass as related to structures in lavas
(5) E. G. Zies, H. E. Merwin, and E. B. Kaltenthaler: Volcanic rocks from Santiagito, Guatemala (presented by E. G. Zies)
(6) J. F. Schairer and H. E. Merwin: Observations on the stability relations of jadeite (presented by J. F. Schairer)
(7) George Kennedy: The effect of pressure on solubility of quartz in water at supercritical temperatures

The afternoon session was convened at 14^h00^m, Clarence S. Ross presiding. The following six papers were presented:

(8) Fred Keller, Jr., Jack L. Meuschke, and L. R. Alldredge: A preliminary report on the Aleutian-Marshall Islands aeromagnetic survey (presented by Fred Keller)
(9) Eugene Callaghan and Charles J. Vitaliano: Type sequence of Tertiary volcanic rocks in the western part of the Great Basin (presented by Chas. J. Vitaliano)
(10) Rustum Roy and E. F. Osborn: Phase equilibria in the system Li_2O-Al_2O_3-SiO_2 (presented by R. Roy)
(11) J. S. Burlew: The dehydration of phlogopite
(12) Felix Chayes: Use of ratios in petrographic correlations
(13) Rustum Roy and F. A. Hummel: Some observations on the inversion of divalent metal pyrophosphates (presented by R. Roy)

Attendance for the day was about 60. The meeting adjourned at about 16^h30^m

JEWELL GLASS, Secretary

APPENDIX K--MINUTES OF THE ANNUAL MEETING OF 1948, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

The meeting was called to order by President Straub at 09^h15^m on April 21, 1948. The newly adopted policy of rotating membership on permanent research committees was announced.

George W. Musgrave, for the Committee on Honors and Awards, announced the Section of Hydrology awards as follows:

Best paper: Vincent J. Schaefer for his paper entitled Properties of Particles of Snow and the Electrical Effects They Produce, published in Transactions of August 1947.

Best first paper: William C. Spreen, for his paper entitled, A Determination of the Effect of Topography Upon Precipitation, appearing in the Transactions of April 1947.

President Straub presented letters to the recipients in token of the certificate of award which will be prepared at a later date.

There being no further business, President Straub introduced the technical papers as follows:

(R1) L. V. Wilcox: Report of the Research Committee on Chemistry of Natural Waters (read by C. S. Scofield)
(R2) H. G. Wilm: Report of the Research Committee on Evaporation and Transpiration (read by Herbert F. Storey, San Dimas Forest Experiment Station)
(1) M. L. Albertson: Evaporation and the boundary layer
(R3) F. T. Mavis: Report of the Research Committee on the Dynamics of Streams (by title)
(R4) S. W. Lohman: Report of the Research Committee on Ground-Water (read by A. N. Sayre)
(2) W. P. Cross: Relation of geology to dry-weather stream flow in Ohio
(3) H. E. Thomas: Artificial recharge by the City of Bountiful, Utah
(R5) François E. Matthes: Report of the Research Committee on Glaciers (by title)
(R6) Merrill Bernard: Report of the Research Committee on Precipitation
(4) Max A. Kohler and Ray K. Linsley, Jr: Recent developments in water-supply forecasting from precipitation (presented by Max A. Kohler)

The session recessed at 12^h00^m.

Chairman Farrow called the afternoon session to order at 14^h00^m; and introduced Vincent J. Schaefer who gave an interesting talk, illustrated by slides and movies, on snow crystals in the laboratory and the sky. The session recessed at 15^h15^m.

Chairman N. C. Grover called the morning session, April 22, to order at 09^h10^m and introduced the following papers and reports:

(R7) P. E. Church: Report of the Research Committee on Lakes (by title)
(6) J. W. Johnson: Characteristics of wind waves on lakes and protected bays (read by Harold Flinsch, Mississippi State College)
(R8) W. C. Lowdermilk: Report of the Research Committee on Land Erosion (by title)
(R9) R. C. Farrow: Report of the Research Committee on Snow
(7) R. L. Parshall: Forecast runoff in Colorado streams, as based on snow-cover measurements (read by M. L. Albertson)
(R10) C. E. Jacob: Report of the Research Committee on Permeability
(8) Don Kirkman: Flow of ponded water in drain tubes in soil consisting of stratified layers
(9) C. E. Jacob and S. W. Lohman: Non-steady flow to a well of constant drawdown in an extensive aquifer (presented by C. E. Jacob)
(R11) L. A. Richards: Report of the Research Committee on the Physics of Soil Moisture (by title)
(R12) C. C. McDonald: Report of the Research Committee on Runoff
(10) C. F. Izzard: A method of analyzing airfield runoff
(11) C. O. Clark: More flood-storage accounting
(12) J. A. Lieberman and M. D. Hoover: Stream-flow frequency changes on experimental watershed (presented by J. A. Lieberman)

The session recessed at 12^h30^m.

The afternoon session was called to order by Chairman Hathaway at 14^h00^m, and the following papers were presented:

(R13) G. W. Musgrave: Report of the Research Committee on Infiltration
(13) Leonard Schiff and F. R. Dreibelbis: Movement of water within the soil and surface runoff with reference to land use and soil properties (presented by Leonard Schiff)
(14) Leon Lassen and E. N. Munns: The influence of vegetative cover on the yield of water (presented by Leon Lassen)

The Chairman then called on Oscar E. Meinzer, President of the Union, who spoke briefly on the growth of the Section of Hydrology.

The Chairman then turned the meeting over to Merrill Bernard, who served as moderator for a forum discussion on the question: To what extent can man's use of the land be made to influence runoff? C. B. Brown, E. N. Munns, G. W. Musgrave, A. N. Sayre, F. F. Snyder, and F. L. Weaver formed the discussion group and presented their various viewpoints in an interesting and instructive manner.

The meeting was adjourned at 17^h00^m.

Subsequent to the Annual Meeting, a group of about 25 members and guests visited Safe Harbor Power plant as guests of the Pennsylvania Water and Power Co., where they enjoyed lunch and an

interesting guided tour and discussion with C. F. Merriam. This was arranged at the invitation John A. Walls, President of the Pennsylvania Water and Power Company, through the courtesy of C. F. Merriam.

RAY K. LINSLEY, JR., Secretary

APPENDIX L--MINUTES OF THE ANNUAL MEETING OF 1948, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Tectonophysics of the American Geophysical Union was held on the morning of April 22, 1948 in Conference Room B, Interdepartmental Auditorium, Washington, D. C. The meeting was called to order by President M. King Hubbert at 09^h00^m. The minutes of the previous meeting were approved as published in the Transactions [v. 28, p. 514, June 1947].

The meeting then proceeded with presentation of the six papers composing the Symposium of Slaty Cleavage and Related Phenomena:

(1) Francis J. Turner: Review of current hypotheses of origin and tectonic significance of schistosity (foliation) in metamorphic rocks
(2) Jacob E. Gair: Cleavage and distortion of stratigraphic thickness in Appalachian folds
(3) Richard H. Jahns: Cleavage in central Vermont (presented by Walter S. White)
(4) Walter S. White: Cleavage in east-central Vermont
(5) A. E. J. Engel: Studies of cleavage in the pre-Cambrian metasedimentary rocks of the northwest Adirondack Mountains
(6) Francis J. Turner: Note on the tectonic significance of deformation lamellae in quartz and calcite

After completion of the Symposium, additional papers were presented as follows:

(7) James T. Wilson: Bending and shear tests on lake ice
(8) D. S. Carder and J. B. Small: Level divergence, seismicity, and reservoir loading in Lake Meade area, Nevada and Arizona
(9) Richard M. Field: Geophysics and geology of geosynclines
(10) H. R. Joesting and J. D. Frautschy: Reconnaissance gravimetric survey of part of the Gulf of Mexico
(11) J. R. Balsley: Preliminary aeromagnetic survey of part of the Gulf of Mexico

The meeting adjourned at about 12^h30^m.

A. E. J. ENGEL, Secretary

SPECIAL SCIENTIFIC MEETING, MARCH 26, 1948

Through arrangements with the Division of Oceanography of the Hydrographic Office of the Navy, and British Admiralty Scientific Service, a special meeting was held in Elihu Root Hall, Carnegie Institution of Washington, 1530 P Street, Northwest, Washington, D. C. on March 26, 1948 at 15^h00^m. Presiding was President O. E. Meinzer who introduced Sir Charles Wright, Scientific Advisor to the Service. He introduced G. E. R. Deacon of the Admiralty Research Laboratory, Teddington, England who presented an address on the work at the Laboratory relating to generation and propagation of ocean waves and swell, the relations between ocean swell and microseisms, and the electrical and magnetic effects of marine currents. Following the presentation, there were questions and discussion from the floor, following which the meeting was adjourned at 16^h15^m. About 110 were in attendance.

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION MARCH 11 TO MAY 10, 1948

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Transferred from Inactive to Active Status

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SPECIAL ANNOUNCEMENTS

Thirtieth Annual Meeting in 1949--It is planned that the Thirtieth Annual Meeting of AGU will be held in Washington on dates to be set between April 20 and May 4, 1949. The closing date for titles and abstracts to be included in the program will be about February 20, 1949. Suggestions relating to the meeting are welcome and may be forwarded to the Office of the Union at 1530 P Street, N. W., Washington 5, D. C., or to J. P. Marble, Chairman of the Committee on Meetings, U. S. National Museum, Washington 25, D. C. Ideas relating to a symposium for a single section or involving several sections are especially welcome.

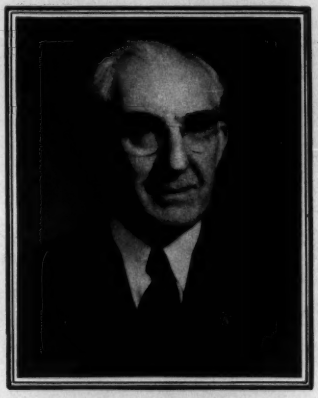
Regional and local meetings--Individuals and groups who desire to arrange regional or local meetings embracing one or more fields of interest of the American Geophysical Union should get into touch with the Office of AGU, 1530 P Street, N. W., Washington 5, D. C., or with J. P. Marble, Chairman of the Committee on Meetings, U. S. National Museum, Washington 25, D. C. Outline of general plans that are beginning to develop are found in the February 1948 issue of the Transactions [pp. 147-148, Appendix 1 of the Minutes of the Executive Committee Meeting of November 28, 1947] and in this issue [page 433, Appendix A of Minutes of the Twenty-Ninth Annual Meeting]. In the latter reference, it is pointed out that the call for such a meeting is to come from the members in the region, and that at least six months should be taken for the development of other than a purely local meeting.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 29 AUGUST 1948 Number 4 Part 1

OSCAR EDWARD MEINZER

Oscar Edward Meinzer was born November 28, 1876, on a farm near Davis, Illinois. He entered Beloit Academy in 1897, and in 1901 was graduated from Beloit College. He later taught science at Lenox College, in Iowa, and carried on graduate studies in geology at the University of Chicago. In 1906 he entered the Geological Survey, and in the same year was married to Alice Breckenridge Crawford, of Hopkinton, Iowa. In 1918, Dr. Meinzer was commissioned a Captain of Engineers and had his orders for overseas duty when the armistice was signed. He received the degree of Doctor of Philosophy from the University of Chicago in 1922, having submitted as his thesis his monumental treatise on "The occurrence of ground water in the United States with a discussion of principles" which was also published as U. S. Geological Survey Water-Supply Paper 489 in 1923. In 1943, he was awarded the Bowie Medal by the American Geophysical Union for his outstanding contributions to the science of hydrology, and in 1946 he was awarded the honorary degree of Doctor of Science by his Alma Mater on the 100th anniversary of the founding of Beloit College.



Oscar Edward Meinzer
President, American Geophysical Union, 1947-1948

Dr. Meinzer was a good student, and early in life displayed the keen methodical mind for which he was noted. At Beloit he was elected to Phi Beta Kappa and was graduated magna cum laude. He was also granted the PhD degree magna cum laude by the University of Chicago.

He was a man of many interests. From his boyhood days on the farm he gained a lifelong interest in farming which was manifested by a deep concern with farm problems, and by his active participation in the management of his own farm properties. He was a student of philosophy, and maintained throughout his life a searching interest in religion. He was an avid traveler, and at the time of his death was looking forward with keen anticipation to attending the Assembly of the International Union of Geodesy and Geophysics in Oslo, Norway; and the Geological Congress in London. He loved people, especially young people, and was a 30-year veteran in the Boy Scouts of America, and was active in the Boy Scout movement in the Washington area nearly since its beginning. For many years he had been a teacher of boys' classes in the Sunday School of the Sherwood Presbyterian Church. But his first interest was in his family and in geology and ground water. In order to combine these two interests he took his family with him on his field trips, often camping in the open. In recent years Mrs. Meinzer has accompanied him on practically all of his many trips from Washington.

Dr. Meinzer was a member of many scientific societies, including Sigma Xi, National Research Council, and was Past-President of the Geological Society of Washington, the Washington Academy of Sciences, the Society of Economic Geologists, and of the Section of Hydrology of the American Geophysical Union. At the time of his death he was President of the American Geophysical Union, President of the International Commission on Subterranean Water, and the American member of the Executive Committee of the International Association of Scientific Hydrology. He was a fellow of the Geological Society of America and of the American Association for the Advancement of Science. He was also a member of the Cosmos Club, and of the Query Club of Washington.

Dr. Meinzer spent the early years of his service with the Geological Survey largely in investigation of the geology and ground-water resources of the arid valleys of the Western States. Many of these valleys were sparsely populated or desert areas but have since become prosperous through irrigation from wells developed as a result of his investigations. Through the succeeding years, until his retirement on November 30, 1946, he investigated the ground-water resources in many of the Western and Mid-Western States and Cuba, and systematized the knowledge of the occurrence and principles of recovery, through wells and springs, of the Nation's great supplies of water that are hidden in the rock formations. Although the science of ground-water hydrology was initially considered more or less academic, its practical importance has become increasingly recognized with the great increase in recent years in the development of ground-water supplies for industries, municipalities, and irrigation. As the need for ground-water investigations grew he trained and supervised the work of dozens of geologists and engineers who came into the Ground Water Division, taking a keen personal interest in the work and problems, both scientific and personal, of each and a humble pride in the accomplishments of his staff. Dr. Meinzer was the leader in the development of ground water for useful purposes. He was the author of many Government publications and articles in scientific and engineering journals. He was the editor and a co-author with 23 associates, of the Volume on "Hydrology," published as Volume IX of the Physics of the Earth Series, National Research Council.

At the time of his death, he was working on a treatise on ground water which was to bring together, under a single cover, his own many papers on the subject as well as the findings of his associates in the Geological Survey, bringing to bear his wide experience and knowledge which gained through his unique position as the father of modern ground-water hydrology. This work was advanced sufficiently so that it is hoped that his colleagues in the Survey, with the aid of his extensive and orderly notes, will be able to complete it.

Dr. Meinzer was apparently in good health and spirits up to the day of his death, June 14, 1948, when he quietly passed away during an afternoon nap. He is survived by Mrs. Meinzer and two sons, Robert William, of Berwyn Heights, Maryland; and Roy Crawford, of New Brunswick, New Jersey; a host of friends, and many students of ground-water hydrology who were initiated to this difficult field through his critical but kindly leadership. His death is a great loss to the sciences of geology and hydrology, and especially to the American Geophysical Union.

A. NELSON SAYRE

Transactions, American Geophysical Union Volume 29, Number 4 August 1948

FLARE TRIANGULATION

F. R. Gossett

Abstract--The method of flare triangulation is based on simultaneous radio-controlled observations by three known and three unknown stations on parachute flares dropped by plane at three air stations between the known and unknown stations. This method is useful where length of line exceeds limit of visibility of ground signals. Length of line is limited only by height and intensity of flare and by range of clear weather visibility.

The method was tested and proved practical in connecting the Bahama Islands to the North American 1927 datum, though almost perfect weather conditions were found to be necessary for field operations.

Flare triangulation is a method for extending triangulation methods of geodetic position determination beyond the limits of sight distance of ground signals. The method is particularly applicable for triangulation connections across wide straits, between the mainland and offshore islands, and between islands in chains of groups. It is limited only by height and intensity of the flare and by range of clear weather visibility. These factors would probably place a practical limit of about 200 miles on length of a line.

Field operation of the flare-triangulation method consists basically of simultaneous radio-controlled observations by three known stations and three unknown stations on parachute flares dropped by plane at three air stations between the known and unknown stations.

The method was tested in this country in the spring of 1946. The scheme as shown in Figure 1 was observed between the Florida mainland and the Bahama Islands with the first part of the project consisting of a test figure for determination of accuracy to be expected from the method. The project was a cooperative project originated by the Hydrographic Office of the United States Navy with participation in both field work and computations by the United States Coast and Geodetic Survey and Army Map Service. The general idea of the method was adapted from the method of W. E. Browne, Lieutenant Colonel of the Royal Engineers, which was used in northern Europe with United States participation at the end of the War.

There were three known stations on the Florida mainland, namely, Congress at Miami, Weed 2 at Delray Beach, and Pisgah near Jenson, Florida. These stations are respectively about 46 and 56 miles apart. The unknown stations in the Bahamas are at Gun Cay, Pinder Point on Great Bahama Island, and at Walker Cay. The distances of these stations from their opposite Florida mainland stations vary from 55 to 110 miles. This made a maximum coverage of the scheme of over 100 miles in two directions, with longest observed line about 125 miles in length. Points over the sea about midway between the known and unknown stations were designated A_1, A_2, and A_3 as target points for flare drops. For example, for each set of simultaneous pointings, an instantaneous position of that flare pointing can be computed as an intersection station from three known stations. Then, with these known flare positions at each of three air stations and with inverse solution between air-station positions, solution of the three-point problem will give a position of the unknown station provided that simultaneous pointings on flare positions are used. Since the flare is a moving target, each set of simultaneous pointings gives only one independent. position at each unknown station. Therefore directions cannot be meaned in the usual manner, and complete position computations are necessary for each pointing. Refinements in accuracy of final adjusted positions are obtained by multiple observations at equidistant circle settings, alternating direct and reversed pointings.

For a test figure, an eccentric instrument was set up near each known station. The position of the eccentric instrument was computed (1) direct by distance and direction from known station; and (2) from the known station through the flare positions and back through eccentric instrument observations as a test of the method.

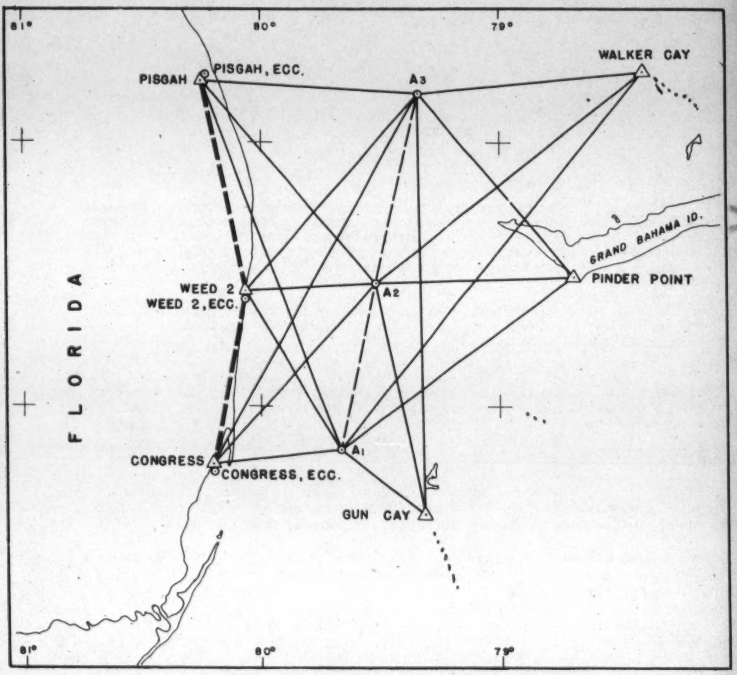


Fig. 1--Flare triangulation, January-April 1946

Since at each station the observations were initialed on a line of known azimuth, one condition equation was introduced. By using this azimuth condition, angles at the flare positions could be taken out, thereby eliminating the laborious task of computing a three-point fix for each set of observations.

Briefly, the field organization consisted of an administrative headquarters office at Masters Field, Miami, a double observing party and two-way portable radio station at each of the six occupied stations, two PB4Y-1 airplanes (four-engined bombers), and three small Navy ships for tending the Bahama Island stations. At each of the three Florida stations, a United States Coast and Geodetic Survey observer and instrument occupied the station center with a Hydrographic Office or Army Map Service observer and instrument on the nearby eccentric station, and at each of the three Bahama stations a Hydrographic Office observer occupied the station center with an Army Map Service observer on the nearby eccentric station. Radio control of observations was at Weed 2, the centrally located mainland station at Delray Beach, Florida.

The airplane was flown at 20,000 ft, and 300,000 candle-power parachute flares were used. Average length of illumination period was four min, 45 sec. Such a flare is visible like a bright star to the naked eye on clear nights and satisfactory for instrument pointings over all distances used (31 to 125 miles).

Successful operation methods were evolved after some experimentation and modification of original plans. After a number of unsuccessful efforts to control all operations from the airplane, radio control of observations was shifted to station Weed 2, which also assisted in navigational

control of flare-drop position. Since clear weather is a prime essential for flare triangulation, special weather reports were obtained from a Naval Air Station aerological unit and from the United States Weather Bureau; and, in addition, starting at $19^{h}00^{m}$, hourly weather reports were received from each of the six observing stations. Plane took off when conditions at all known stations were favorable and one or more of the unknown stations reporting favorable and improving conditions. It usually required about 1 1/2 hours after take-off orders for the plane to get into the air and to the first flare station. All stations were advised when the plane took off so as to set up instruments and turn on azimuth lights. The plane established radio communications with the ground stations as soon as possible, advising of plane's location and approximate time for next flare, "flare away," and "flare ignited." At times, these data had to be relayed, but could usually be heard direct by the radio control station. Voice-radio communication was generally most satisfactory.

Any flare which could be used for pointings was always visible to the naked eye at the radio-control station. All stations were furnished with precomputed directions and angles of elevation to target positions of flare drops. However, due to the plane's navigational uncertainties, the flares were very seldom in the field of view of telescope when ignited. Pointings were perfected by sighting by eye, and once a flare was picked up, its drift was sufficiently slow that it was never lost from the telescope between readings during illuminated period of flare. Watches at all stations were synchronized by radio while plane was appraching first drop station. Before each flare drop, there was radioed to all stations information which included the name of next drop station, the flare number, the plate circle setting for next position, and position of the telescope. The systems used for the plane's drop runs were to fly along the line of target positions as A_1, to A_2, to A_3, then A_3, to A_2, to A_1 and continue repetitions of these runs except where necessary to fill in for misses and duds. While plane the was appraching each target position, the observer made plate setting and made pointing and reading on his azimuth light initial, then set theodolite for expected position of flare. After each set of flare pointings, observation was again made on initial. The telescope remained in one position throughout a single flare and was reversed for the next flare at same target station. There was either a loudspeaker at each station, or in most cases, the observers wore radio headphones. As soon as a flare ignited, the radio control station took up the count, which went about as follows: "Flare ignited at A_1, 45 sec to first pointing, 30 sec, 20 sec, 10 sec, 5, and, 4, and, 3, and, 2, and 1, and mark." The observer followed the flare with alidade unclamped until the 10-sec warning, then clamped and kept flare centered with the tangent screw, stopping the screw sharply on the mark, and reading the instrument. The recorder recorded the flare number, target station, position number, position of telescope, time of mark, and observer's readings. Pointings were taken at intervals of 45 sec, and usually four to six pointings were obtained on each flare. With all observers experienced, this interval could probably be reduced to 30 sec. Stations reported the number of successful pointings and flare-bearing data to the radio-control station immediately after each flare.

It was found necessary to assist the plane in getting on the flare target with ground control. This was done by having each station report immediately after each flare the number of whole degrees that the flare was right or left of the precomputed target bearing from that station. A specially prepared plotting board was maintained at the radio-control station where these angles were quickly plotted and the plane advised of distance and bearing which last flare was from the target position. As this information was usually available in less than two min after flare, it was used to correct the plane's course and timing in order to drop the next flare closer to the target position. This ground-control system could be still further improved by having two or more separate instrument stations report the true bearing of the flare to the plane on some other wave length immediately on ignition for plotting in the plane. A survey ship with its searchlight pointing upward and maintaining position at the middle target position might furnish adequate target control.

A total of 128 flares were dropped, of which 18 were duds, and nine were a special daylight test. Flares up to one million candlepower were included in the daylight test but were visible only up to about 25 miles, proving daylight observations to be impractical. During the two months of flight operations on the project, flares were dropped on 11 nights, but only on the last three nights' operations were conditions favorable at all stations. Most of the acceptable observations were made on April 3, 1946 when weather conditions were perfect.

After record books were computed to the zero initial, and checked, each pointing was abstracted as a direction on a list of directions for each instrument. Simultaneous pointings on lists from each station are identified by six-digit time groups in hours, minutes, and seconds of standard time. A tabulation was made up by target stations showing number of pointings of each instrument on each flare. Each flare position was also plotted graphically on a polyconic projection.

From the tabulation and plotted positions, observations were selected for computation from flares which had a minimum of four simultaneous pointings from all six stations. The flares selected were evenly distributed by plate circle position settings, by direct and reversed pointings, and by proximity to target position. Flares were selected to give 32 independent positions at each air station, 32 positions of each eccentric instrument at Florida stations for test of method; and, using the same 32 air-station positions, to give 32 independent positions of each of the three Bahama stations.

The computing necessary for the flare-triangulation method is unusually heavy because of the many independent computations required. It has been suggested that comparable accuracy could be obtained if observations were made simultaneously at three eccentric stations in addition to the true station, and reduced and meaned to one direction. Then, if four flares were used at each air station with three pointings on each flare, 12 positions instead of 32 could be computed for each station in the scheme. This would decrease the number of flares, the operating time and amount of computations, but would require additional instruments and observers standing by for suitable weather.

Since one of the primary objectives of this project was to test and develop methods, a brief summary of position closures will probably be of interest and are shown in Table 1.

Table 1--Position of summary closures

Station	Accuracy
Pisgah, Eccentric	1/ 72,000
Weed 2, Eccentric	1/150,000
Congress, Eccentric	1/108,000
Gun Cay	1/ 25,000
Pinder Point	1/ 30,000
Walker Cay	1/ 10,000

The method is considered practical from a field operational standpoint. The principal operational difficulties encountered were unfavorable weather, plane radio failures, and erratic aerial navigation. Almost perfect weather conditions are essential. There can be no intervening clouds in the lines of sight extending from ground level to about 20,000 ft and over areas well over 100 miles in either direction. Because of the large outlay of perconnel and equipment involved, a large percentage of adverse weather conditions may make the costs prohibitive in both time and money. Exhaustive weather studies should precede any future project to determine the feasibility of flare triangulation and the most favorable season for field work.

U. S. Coast and Geodetic Survey,
Washington, 25, D. C.

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DISCUSSION

B. K. Meade (U. S. Coast and Geodetic Survey, Washington, D. C.)--The position closures of the three eccentric stations on the Florida Coast indicate that flare triangulation is an excellent method for extending triangulation over long lines. These closures of four, five, and eight ft are within the limits required for first-order triangulation. The closure of the middle station (Weed 2) is smaller than the closures of the outside stations. No small angles were involved in the triangles at this middle station, therefore small errors in observation have less effect on the adjusted result.

The average corrections applied to the observed directions are shown in Table 2.

Table 2--Table of corrections

Station	Average corrections	
	Center station	Eccentric station
	"	"
Congress	2.3	2.8
Weed 2	2.3	2.3
Pisgah	2.6	4.3

The maximum correction for all observations was between eight and nine sec.

From 32 flare positions in each area, three rejections were made because of large corrections. The position of each eccentric station is then a mean of 29 positions.

The above comments and statistics refer to the Florida stations only. Closures of stations in the Bahama Islands were less accurate. In some sets, observations were incomplete due to inability to see flares and several observations were rejected because of excessive corrections.

Transactions, American Geophysical Union Volume 29, Number 4 August 1948

A TWO-COMPONENT SHOCK RECORDER

H. E. McComb

Abstract--This paper describes a simple shock recorder that has been designed and built by the United States Coast and Geodetic Survey.

For a number of years engineers and seismologists interested in the effects of destructive earthquakes on engineering structures have indicated that it would be desirable to have a large number of inexpensive shock recorders well distributed in seismic areas to furnish more reliable information on earthquake magnitudes. About a year ago the United States Coast and Geodetic Survey began experimental work on such an instrument, having decided that the general specifications should be about as shown in Table 1.

Table 1--Specifications for a two-component shock recorder

Item	Specification
Pendulum period	0.5 sec
Damping	3:1 or better
Maximum amplitude of steady mass	4 to 6 cm
Trace magnification	3x
Lever system	one lever, no linkage
Components	2 horizontal
Time control on record	none
Paper speed operating	1 cm/sec
Paper speed, stand by	10 cm/day
Capacity of recorder	10 operations
Cost per component	not to exceed $150

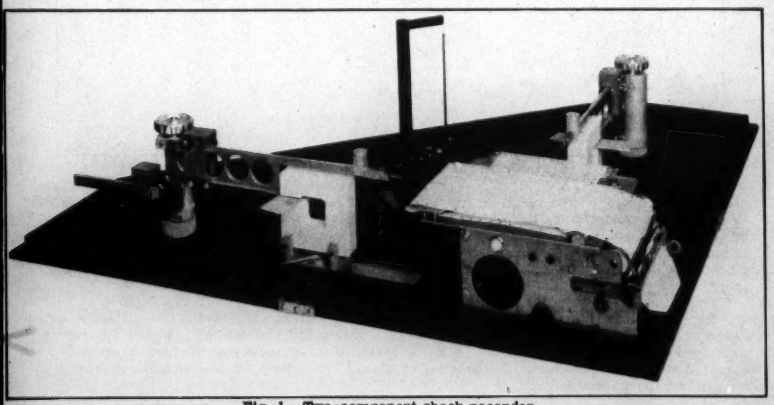

Fig. 1--Two-component shock recorder

In spite of the fact that all of the items of the specifications could not be met, and at the same time produce finished instruments in quantity at the low cost indicated, an attempt was made to

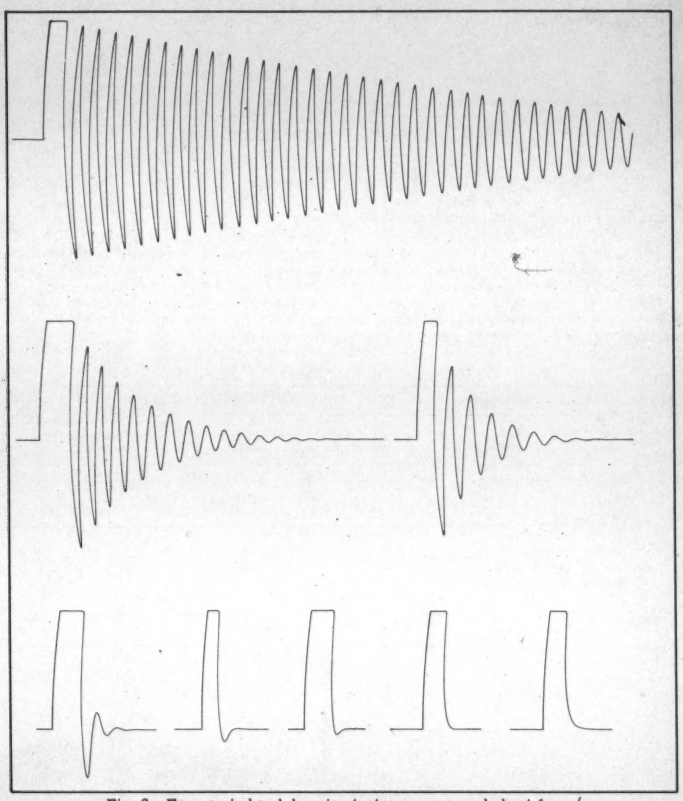

Fig. 2--Free period and damping tests; paper speed about 1 cm/sec

carry out the project. The resulting instrument, shown in Figure 1, was made by J. B. Krahe and the tests were conducted by H. H. Howe, T. H. Pearce, and W. E. Wiles. The boom is supported by two flat springs under tension; static magnification is adjustable over a wide range; damping is magnetic, also adjustable. Two horizontal components record in ink on the same tape. The instrument is provided with a pendulum starter, and the recorder stops automatically after one minute; this cycle can be repeated about 15 times.

Repeated tests indicate that pen friction is small and that the stiffness of the springs is sufficient to maintain a constant zero position within a fraction of a millimeter. Figure 2 shows an undamped decay curve and samples of damping tests. It is proposed that the instrument be operated at 0.6 to 0.8 critical. The damping vane is of 1/16 inch aluminum and operates in the air gap of a permanent magnet.

It has been almost impossible to obtain from the literature, accurate basic information on the strength and distribution of the field in the air gaps of magnets of different designs. Fortunately, a new instrument, known as a gaussmeter, has been developed commercially within the past three

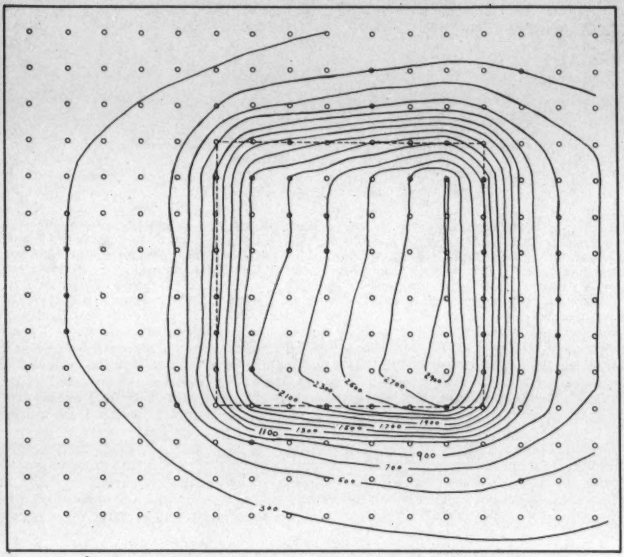

Fig. 3--Field distribution in air gap of one of the magnets investigated, face of magnet adjacent to air gap, indicated by dotted line, is about one inch square; small circles indicate points at which field was measured by means of a gaussmeter

years, and this instrument has made it possible to explore in detail the fields in the air gaps of several magnets. The results of one of the tests are shown in Figure 3. The distribution of the field depends to a large extent upon the manner in which magnetization has been carried out, no two samples giving the same pattern.

We have accumulated a vast amount of data on damping forces and we believe that the basic information obtained is in itself sufficient justification for the time expended in developing this shock recorder.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

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EFFECT OF SHIP MOTION UPON MEASURING CLOUD HEIGHT WITH A SEARCHLIGHT

Garret L. Schuyler

Abstract--Assuming there is no roll or pitch of ships from which cloud-height measurements are made, three equations for the cloud height have been derived. These are equations of the utmost generality, from which all solutions of possible interest are readily had as special cases by using progressively simpler assumptions. After satisfactorily demonstrating that errors from the ship's roll and pitch can be calculated without regard to the method used in estimating cloud height, such errors are calculated by use of direction cosines.

A proposal by BILHAM [1947], that a new method of measuring cloud height with a searchlight be used on weather ships with 200 ft base-line installations, closes with the remark: "Difficulties associated with the rolling and pitching of ships are of course not considered in this connection." Even for the orthodox vertical-beam method, the errors in cloud-height measurements caused by roll and pitch of the ship carrying the searchlight seem not to have been adequately investigated.

Referring to Figure 1, assume that on the centerline of a ship a searchlight at distance L from the observer has its beam fixed at an elevation α, is trained at an angle β, and throws, on a cloud ceiling of height h, a spot of light of which the observer may measure (in a system of coordinates fixed to the ship) either elevation E or azimuth θ (from the searchlight) or slant angle ϕ subtended by the beam.

Formulas for determining h are

$$\cot^2 E = (L/h)^2 - 2(L/h) \cot \alpha \cos \beta + \cot^2 \alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\cot \theta = \tan \alpha \operatorname{cosec} \beta (L/h) - \cot \beta. \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

(or the equivalent [BILHAM, 1947 a and b] $(h/L) = \tan \alpha \sin \theta \operatorname{cosec} (\theta + \beta)$.

$$\cot \phi = \sin \alpha (1 - \cos^2 \alpha \cos^2 \beta)^{-1/2} (L/h) - \cot \alpha \cos \beta) \quad \ldots\ldots\ldots\ldots (3)$$

In practice, however, the elevation angle method is used only, with $\beta = 0°$, or with $\alpha = 90°$, making (1) respectively [MIDDLETON, 1939, 1942 p. 172] $\cot E = (L/h) - \cot \alpha$, and $\cot E = (L/h)$.

The azimuthal method (2) was proposed [BILHAM, 1947 a and b] because when h/L is equal to or greater than 2, an error of 1° in θ has usually much less effect than an error of 1° in E. But as shown by others, this is more than offset by comparatively greater inaccuracies in measuring θ at high elevations (Bibby pointed this out in a letter to the Editor, published in the Meteorological Magazine in 1947). This is due to the fact that a spot of angular diameter ψ subtends an azimuth not of ψ but of $\psi \sec E$.

The slant angle method (3) appears not to have been proposed. It is included here for completeness. It will be observed that (3) properly reduces to $\cot E = (L/h) - \cot \alpha$ if $\beta = 0°$.

For a specific inclination of the searchlight beam to the plane of the horizon, the visible length of beam varies directly as the ceiling height h. Conversely, therefore, the estimated value of h (determined by using a system of coordinates fixed to the rolling ship) must vary directly as the visible length of beam changes while the ship rolls to angle R and pitches to angle P. So regardless of the method actually used in estimating h, we can determine the proportional error in h merely by computing the proportional change in the visible length of the searchlight beam.

Let L_1 be a line directed along the searchlight beam; L_2, a line directed along the vertical; L_3, a line directed perpendicular to the deck; L_{12}, the angle between line L_1 and line L_2; L_{13}, the angle between line L_1 and line L_3; a_1, b_1, and c_1, the direction cosines of L_1 relative to ship

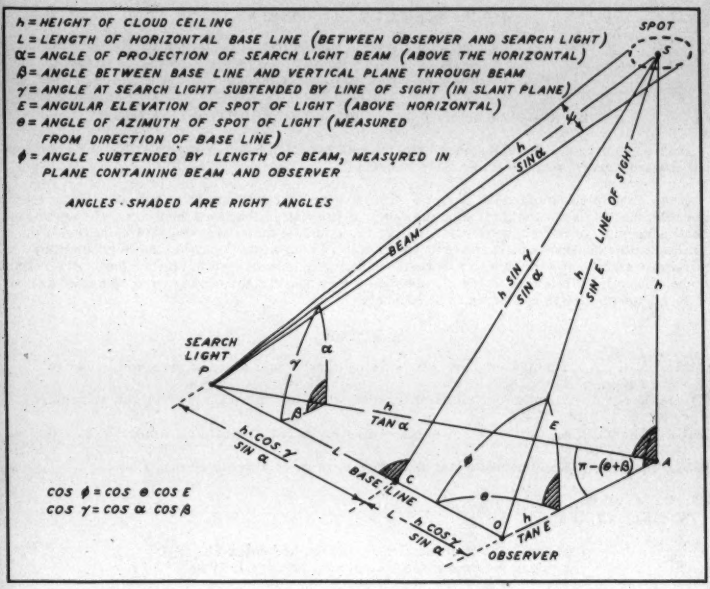
h = HEIGHT OF CLOUD CEILING
L = LENGTH OF HORIZONTAL BASE LINE (BETWEEN OBSERVER AND SEARCH LIGHT)
α = ANGLE OF PROJECTION OF SEARCH LIGHT BEAM (ABOVE THE HORIZONTAL)
β = ANGLE BETWEEN BASE LINE AND VERTICAL PLANE THROUGH BEAM
γ = ANGLE AT SEARCH LIGHT SUBTENDED BY LINE OF SIGHT (IN SLANT PLANE)
ε = ANGULAR ELEVATION OF SPOT OF LIGHT (ABOVE HORIZONTAL)
θ = ANGLE OF AZIMUTH OF SPOT OF LIGHT (MEASURED FROM DIRECTION OF BASE LINE)
φ = ANGLE SUBTENDED BY LENGTH OF BEAM, MEASURED IN PLANE CONTAINING BEAM AND OBSERVER
ANGLES SHADED ARE RIGHT ANGLES
SPOT
S
BEAM
LINE OF SIGHT
h/SIN α
h SIN γ / SIN α
h/SIN ε
h
SEARCH LIGHT
P
α
γ
β
h/TAN α
ε
φ
θ
π − (θ+β)
A
C
O
h/TAN ε
h·COS γ / SIN α
L
BASE LINE
L − h·COS γ / SIN α
OBSERVER
COS φ = COS θ COS ε
COS γ = COS α COS β

Fig. 1--Diagram illustrating methods for measuring height of clouds

coordinates; a_2, b_2, and c_2, the direction cosines of L_2 relative to absolute coordinates; and a_3, b_3, and c_3, the direction cosines of L_3 relative to absolute coordinates.

By derivations omitted here, it is not difficult to show that, where by definition cos C = cos R cos P, these direction cosines have the following values:

$$a_1 = \cos\alpha \sin\beta \qquad b_1 = \cos\alpha\cos\beta \qquad c_1 = \sin\alpha$$

$$a_2 = 0.000 \qquad b_2 = 0.000 \qquad c_2 = 1.000$$

$$a_3 = \sin C\ \sin R/\sqrt{\tan^2 P + \sin^2 R} \qquad b_3 = \sin C\ \tan P/\sqrt{\tan^2 P + \sin^2 R} \qquad c_3 = \cos R\ \cos P$$

As the ship moves from its upright position the visible length of the searchlight beam will change in the ratio $k = h \sec L_{13}/h \sec L_{12}$, or $k = \cos L_{12}/\cos L_{13}$. Using direction cosines, this becomes

$$k = (a_1a_2 + b_1b_2 + c_1c_2)/(a_1a_3 + b_1b_3 + c_1c_3) \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The error in estimated ceiling caused by roll R and pitch P is

$$h(k - 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Example: Let $\alpha = 80°$, $\beta = 45°$, $R = -30°$, and $P = -7°$.

The direction cosines are

$$0.122 = a_1 \quad 0.122 = b_1 \quad 0.985 = c_1$$

$$0.000 = a_2 \quad 0.000 = b_2 \quad 1.000 = c_2$$

$$-0.496 = a_3 \quad -0.122 = b_3 \quad 0.860 = c_3$$

$$k = (0 + 0 + 0.985)/(-0.061 - 0.015 + 0.845) = 0.985/0.771 = 1.28$$

So the error caused by this rather extreme roll and pitch has therefore a value of 28 per cent of h. Larger errors would seem unlikely to occur.

Even in ship coordinates the position of the spot of light will change by a readily calculable amount as the ship's motion lengthens and shortens the visible length of the beam. The record of a continuously recording photo-electric ceilometer would be disturbed. But, if one instructs operators to confine observations to times when the ship is very nearly upright, and helps them by appropriate signals at such times, it is believed that ship motion need not be the factor determining the success or failure of measuring cloud height with a searchlight on shipboard. Limited baseline length seems to be the most serious handicap.

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COMPUTATION OF MAXIMUM RAINFALL IN THE WILLAMETTE BASIN

George W. Platzman

Abstract--Maximum average depths of storm rainfall are computed for the 11,200 square-mile area drained by the Willamette River in western Oregon. These depths may be taken as estimates of maximum possible rainfall rates that could conceivably be produced by one of the general winter storms characteristic of the Pacific Northwest, and apply to durations between six and 96 hours. Statistical procedures were employed in establishing the relation between rainfall and rainfall indices; in this respect the methods described differ from most existing techniques.

Introduction--Effective utilization and control of water resources are contingent upon knowledge of climatological and meteorological factors that determine seasonal, geographical, and storm distributions of rainfall. Problems of utilization and control can be divided broadly into two phases, planning and operation. Among the important aspects of planning is the capacity design of dams and spillways, which involves estimates of maximum potential stream discharge, in turn related to estimates of maximum potential rainfall.

As part of a comprehensive program of flood control and water utilization in the Columbia River Basin, the U. S. Army Corps of Engineers has developed estimates of maximum potential rainfall for a large number of tributary watersheds, including the Willamette River Basin, Oregon. In this paper are outlined a method and results leading to computation of maximum rainfall in the Willamette Basin according to studies made in the Portland, Oregon District of the Corps of Engineers.

General--The Willamette Basin in western Oregon is part of the chain of fertile inland valleys that extends along the entire West Coast of the United States and includes the San Joaquin and Sacramento Valleys in California. The Willamette River rises on the northern slopes of the Calapooya Mountains that join the Coast Range on the west and Cascades on the east, and flows northward into the Columbia River at Portland (see Fig. 1). Forming two essentially parallel barriers to the eastward flow of air, the Coast and Cascade ranges cause a profound influence on the climate of the valley. The former range, which parallels the Coast at a distance of roughly 30 miles, has an average elevation of about 2000 ft and maximum elevations slightly over 4000 ft. In contrast, the more massive Cascades, with an approximately north-south axis lying some 100 mi inland, have an average elevation of 6000 ft and isolated peaks rising over 10,000 ft above sea level.

Major rain-producing storms in the Pacific northwest occur during late fall, winter, and early spring months. These storms are produced by intense cyclonic disturbances that move eastward across the northeastern quadrant of the Pacific Ocean and upon reaching the American continent encompass a wide area, often including Washington, Oregon, and northern California. Large amounts of precipitation on the coast and contiguous inland areas are generally associated with strong southwesterly flow and high dew point in the invading maritime air. Comparison of mean annual isohyets with elevation serves to illustrate the great significance of topography. This fact is well known in relation to areal distributions of normal annual precipitation, which show maxima at high elevations and minima in valleys. Proximity to the coast is also an important factor. Thus, Astoria at the mouth of the Columbia River, receives 77 inches of rainfall annually, while Portland, 100 river miles upstream, receives 42 inches.

Rain formation is dependent upon establishment of vertical components in the generally horizontal motion of air currents, leading to cooling and condensation of water vapor. Such vertical motion can occur (1) when a strong horizontal current is forced to ascend a mountain range (orographic ascent) or a wedge of colder air (frontal ascent), and (2) when relatively stagnant air is transformed into one or more convective cells, possessing characteristic circulations of strong ascending and descending currents. Major rainstorms in western Oregon result from combined action of convective, orographic, and frontal processes. Little is known about the quantitative role of convection in orographic rain [BONACINO, 1945], and although there can be no doubt that this process is operative, many observers favor the view that its importance is relatively minor for general cyclonic storms on the West Coast.

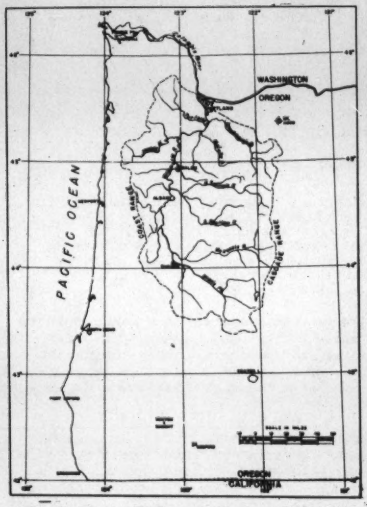

Fig. 1--Map of Willamette Basin and vicinity

An example of the computation of stable orographic precipitation has been given by BJERKNES [1940] in which the computations lead to distributions of "windward" orographic intensities. Another method is utilized by the Hydrometeorological Section of the United States Weather Bureau in a report on maximum precipitation over the Los Angeles area, California [U. S. WEATHER BUREAU, 1946]. The method of the Hydrometeorological Section leads to average depths of rainfall over an area bordered by the orographic barrier, and constitutes an application of the moisture-storage principle formulated by SHOWALTER [1944].

In connection with the Willamette Basin study, an independent appraisal of existing theoretical techniques for computation of orographic precipitation led to the belief that an appropriate rainfall formula could be developed more suitably by means of a statistical method, as will now be described.

Method--The procedure whereby maximum possible average depths of rainfall over the Willamette Basin were determined may be arranged in three steps: (1) Establishment of a rainfall formula relating rainfall to selected meteorological indices (wind velocity and dew point); (2) estimation of maximum values of the selected indices; and (3) computation of maximum rainfall by extrapolation from rainfall formula.

Justification for this procedure, adopted from methods developed by the Hydrometeorological Section of the United States Weather Bureau, is based upon the assumption that reliable estimates of maximum rainfall can be established from estimated maximum values of related meteorological factors. In support of this assumption is the fact that well-selected observations of such elements as wind and dew point possess greater areal representation than rainfall observations. Further, since precipitation measured at a point is a discrete phenomenon in both time and space whereas wind and dew point are continuous, the latter can be more frequently observed and are more susceptible to reliable statistical analysis.

Establishment of rainfall formula--It has been widely noted that high rates of storm rainfall on the West Coast of the United States are associated with the concurrence of high wind velocities with westerly component, and high moisture charge extending through a deep layer in the storm air mass. Following principles established in reports of the Hydrometeorological Section on the Los Angeles area, California [U. S. WEATHER BUREAU, 1946] and the Sacramento Basin, California [U. S. WEATHER BUREAU, 1943], it was assumed that wind velocity and dew point observed at a representative station would serve as appropriate indices to Willamette Basin rainfall.

As a first step in establishing the rainfall formula, a time interval of six hr was chosen in terms of which values of rainfall and of the rainfall indices were expressed. Choice of this time interval was governed largely by the nature of basic data available and by the requirements of the study. As to the former, records of hourly accumulations of rainfall were available from published data of the Hydrologic Network of recording precipitation gages maintained jointly by the Weather Bureau and the Corps of Engineers for the period subsequent to January 1940, while hourly observations of wind velocity and dew point are taken at a number of Airways stations in western Oregon. However, the requirements of the study called for duration-depth values of maximum precipitation that are multiples of a six-hr unit of time, as prescribed by the six-hr time unit of the unit hydrographs from which the computed flood hydrographs are ultimately derived. Because of pronounced irregular time lags between instantaneous values of rainfall intensity and re-

lated meteorological variables, and the resultant poor intercorrelation between these variates, the six-hr time unit was considered the smallest unit that could be employed without obscuring possible relations between the rainfall and indices.

Using the hypothesis that a representative surface observation of dew-point temperature is a reliable index of the moisture content of an air mass during storm conditions, a survey was made of stations recording observations of this element in or near the Willamette Basin. The decision was to employ the record of Sexton Summit, a first-order Airways station in the Rogue River Basin approximately 55 airline mi from the coast and at an elevation 3855 ft above sea level (see Fig. 1). Selection of the Sexton Summit record was based on consideration of exposure of the station, length and adequacy of record, and frequency of observations. The station is located at the crest of a nearly symmetrical dome-shaped prominence and is well exposed in relation to surrounding topography. It is sufficiently near to the Oregon Coast to serve as a reliable index to properties of invading oceanic air masses before these air masses undergo appreciable transformation. Hourly dew-point observations have been made at Sexton Summit since January 1932, thus providing about 15 yr of continuous record.

The degree of correlation between Sexton Summit dew points and the concurrent precipitable water content of the prevailing air mass was examined by analyzing a total of 49 upper-air soundings (taken at Medford) that reached an elevation of six km (approximately 20,000 ft) during the month January 1945. For each of these soundings the precipitable water content of the air layer between 1175 m (elevation of Sexton Summit) and six km was computed, and correlated with an average of the two dew-point observations made on the hours closest to the time of the radiosonde ascent. The product-moment correlation coefficient between precipitable water content and Sexton Summit dew point was found to be 0.89 for the 49 soundings selected (of which some were not associated with storm conditions).

Considerable difficulty was experienced in selecting an appropriate index to the rate of inflow of moisture. Attempts to utilize pilot-balloon observations were very soon abandoned because of the inadequacy of these records, particularly during storm conditions. Wind observations by radio direction finder have been made at Medford twice daily since November 1944; it was believed, however, that the period of record is too short and the observations too infrequent for reliable statistical analysis, especially in view of the selected basic six-hr time interval. Several techniques were studied, including the preparation of three-hourly pressure maps. Two indices appeared to produce the most reliable results: (a) The instantaneous pressure difference between two stations (Newport and North Bend) on the coast, determined from original barograms, and (b) hourly wind velocity observed at Sexton Summit, taken without regard to direction. For a number of reasons the latter index was selected.

A product-moment correlation coefficient of 0.85 was found between Sexton Summit surface wind velocity and the simultaneous 5000 ft free-air velocity as determined from original records of pilot-balloon observations at Medford. Only cyclonic or storm conditions were considered in establishing this relation, derived from a compilation of 86 separate cases. Based on this study, the linear regression between Sexton Summit surface-wind velocity S and Medford 5000 ft free-air velocity M was found to be, roughly $M = S + 6$ (miles per hour) in the range $S = 0$ to 40 mph, each velocity being taken without regard to direction.

The use of a six-hr unit of time automatically limits the storm occurrences required for statistical analysis to the period subsequent to the first publication of data of the Hydrologic Network of recording precipitation gages, namely, January 1940. Selection of storm periods for the purpose of establishing a relation between rainfall indices was made on the basis of three specifications: (1) The storm must occur during or after January 1940; (2) the storm must rank high for short- and long-period precipitation over the Willamette Basin; and (3) the index-wind velocities and dew points must rank high. Five storm periods were selected to meet these criteria and to serve for the statistical analysis. Dates, durations, and numbers of six-hr periods in these storms are as shown in Table 1. The storms are placed in their approximate order of magnitude, the most intense first.

Standard statistical procedures, involving graphical methods, were employed to determine the most suitable joint relation between r (six-hr accumulated Willamette Basin rainfall), w (six-hr average Sexton Summit wind velocity), and d (six-hr average Sexton Summit dew point). Application of these methods led to the selection of the following type of relation:

Table 1--Data on the five storm-periods selected

Date	Duration	Number of periods
	hr	six-hr units
Dec. 25-29, 1945	120	20
Nov. 13-16, 1941	96	16
Nov. 13-17, 1942	120	20
Dec. 15-19, 1941	120	20
Nov. 22-26, 1942	120	20
Totals	576	96

$$r = (\alpha + \beta w^2)(\gamma + \delta d)$$

where α, β, γ, and δ are constants.

The presence of a quadratic velocity term is not entirely consistent with what may be expected on theoretical grounds, but examination of the basic data indicated that it may be explained as owing to short-period superposition of frontal rainfall. A linear relation suffices to account for the purely orographic component, which contributes the major part of total volume of rainfall, but the tendency for high values of wind velocity to be associated with frontal increments of rainfall introduces a nonlinear overall relation between these variates.

Numerical values of the constants in the preceding rainfall formula were established by applying the least-squares criterion to the 96 triads r, w, and d of basic rainfall and index data. After some simplification the following formula was obtained:

$$r = 17w^2d \times 10^{-4} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where r = six-hr accumulated rainfall averaged over the Willamette Basin (11,200 sq mi), expressed in points (hundredths inches), w = concurrent six-hr average Sexton Summit wind velocity in mi/hr, and d = concurrent six-hr average Sexton Summit dew point in degrees F.

Maximum index values--Twelve years of hourly dew-point observation at Sexton Summit were available for estimation of maximum duration of maximum dew points. It was assumed at the outset that the maximum storm over the Willamette Basin should be confined to the four-month period November through February. Aside from climatological and meteorological evidence in support of this assumption, there is the important factor of necessary antecendent conditions that are recognized as characteristic of major flood-producing storms. Most critical of these conditions are the presence of an extensive snow cover and the prior reduction of infiltration rates, resulting from general antecedent precipitation.

From a complete survey of the 12-yr record at Sexton Summit, enveloping maximum dew-point durations for the winter season (November through February) were established. These values are based on 48 station months of record or approximately 35,000 hourly observations. Their reliability was tested by examination of 34 station months of hourly observations at four stations on the Oregon coast (Tongue Point Naval Air Station, Yaquina Head, North Bend Naval Air Station, Port Orford,) and 36 station months of three-hourly observations at Brookings, Oregon. When appropriate reductions to sea level were made for the Sexton Summit values, it was found that the latter exceeded all coastal values without exception. Thus, the absolute maximum (winter) dew point in the Brookings record is 62°F on November 5, 1941, while the absolute maximum in the Sexton Summit record is 56° F on November 10, 1934 (which occurred prior to establishment of the station at Brookings). If the latter value is reduced to sea level by means of a pseudo-adiabatic lapse rate, a value of 65 to 66° F is obtained. Although a nine-or ten-degree reduction of the 56° observation at Sexton Summit may be too large, comparison between simultaneous maximum occurrences at Brookings and Sexton Summit indicated that an average reduction of at least eight degrees is necessary. The Sexton Summit maximum dew point reduced to sea level would then be 64°F. For 72 hours duration the data indicated that a dew point (at Sexton Summit, winter) could be maintained at or above 44°F.

Similar studies led to the establishment of enveloping maximum wind velocity durations. Since observations of wind velocity do not possess the high degree of uniformity that characterizes dew-point observations, allowance was made in some instances for the presence of marked fluctuations which the record indicated to be nonrepresentative.

Computation of maximum rainfall--Maximum precipitation is computed by arranging the enveloping maximum dew-point duration values in the form of time distributions and applying the rainfall formula [BJERKNES, 1940].

Examination of concurrent dew-point and wind-velocity time distributions for selected storm occurrences led to the conclusion that concurrence of maximum values of these elements could justifiably be assumed as a feature of the maximum storm. Symmetrical time distributions were employed in the computation since this arrangement produces the greatest rainfall depths and since conclusive evidence was lacking to show that such a distribution is improbable.

Maximum precipitation computed in this manner was rearranged to produce maximum depth-duration values. These, tabulated in the second column of Table 2, were then adjusted to allow for the fact that the basic rainfall formula, statistically derived, in general underestimates high rainfall intensities and overestimates low intensities. The adjustment consisted in multiplying these values by the average ratio of observed to computed depth-duration values for the five storms employed in the statistical analysis. Values of this ratio are shown in the third column of Table 2, and the final values of maximum precipitation over the Willamette Basin are tabulated in the fourth column.

Table 2--Maximum precipitation from depth-duration data

Duration (1)	Preliminary values of maximum rainfall[a] (2)	Ratio, observed to computed maximum rainfall (3)	Final values of maximum rainfall (4)	Maximum observed rainfall in Willamette Basin[a] (5)	Ratio (4) to (5)[b]
hr	in		in	in	
6	2.1	1.11	2.3	1.5	1.53
12	3.3	1.09	3.6	2.6	1.40
18	4.4	1.07	4.7	3.5	1.34
24	5.3	1.05	5.6	4.3	1.29
36	6.7	1.02	7.0	5.6	1.25
48	7.8	1.00	8.0	6.5	1.23
72	9.4	1.00	9.5	7.7	1.23
96	10.5	1.00	10.5	8.3	1.26

[a]Rainfall depths apply to entire Willamette Basin, 11,200 sq mi.
[b]Curves smoothed graphically.

Although the time distributions of dew point and wind velocity constructed from the corresponding duration curves result in a symmetrical distribution of computed intensities of maximum precipitation, some freedom in the arrangement of rainfall increments is justified. Gross departures from a symmetrical intensity distribution are probably not characteristic of the maximum storm, but it may be noted that the peak intensity in a general storm of the maximum-storm type tends to occur after a prolonged period of moderate to heavy rainfall and often marks the cessation of high intensities. The intensity distribution may thus show a gradual rise to the peak, followed by a more or less marked decline to the end of the storm period.

Meteorological evidence has been generally accepted as indicating that the maximum winter storm over selected major drainage basins in the Pacific Northwest is necessarily associated with general storm conditions, that is, with widespread storminess and heavy rainfall. The foregoing determination of maximum rainfall depths for the Willamette Basin should be considered as applicable only to such a general storm type. In the present state of knowledge of local storm phenomena, quite different and often highly empirical procedures must be utilized in formulating specific estimates of maximum rainfall rates for small drainages, 500 sq mi, or less, in size. It should not be inferred from this, however, that maximum rainfall rates for small areas are necessarily produced by storm conditions that are essentially different from those of the general storm. Quantitative information relative to this problem is meagre, but it is the writer's opinion that apart from very short durations (less than three hr) and very small areas (less than 100 sq mi), maximum rainfall rates for drainages in the Pacific Northwest can be definitely associated with disturbances of the general storm type. Maximum depth-duration values for the total Willamette Basin (11,200 sq mi) thus serve as an important framework in estimating corresponding values for specific subdrainages.

Acknowledgment--The writer has received much encouragement and support from people in the Portland, Oregon District of the Corps of Engineers, and most particularly extends his thanks to John M. Allison. He is also especially indebted to Morris Larson and Stanley Miller, and to Kathleen Hollenbeck, Marion Harju, Helen Jones, Kathleen Walters, Wendell Maccoby, and Richard Noland who, from time to time have given advice or assisted in the technical analysis. Larson aided greatly in preparing the manuscript and has supplied many helpful criticisms.

It is a pleasure also to acknowledge fruitful discussions with members of the Hydrometeorological Section of the United States Weather Bureau, whose collective counsel has proved invaluable.

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Transactions, American Geophysical Union Volume 29, Number 4 August 1948

ON A LUNAR BI-FORTNIGHTLY TIDE IN THE ATMOSPHERE

Reid A. Bryson

Abstract--By studying the latitude anomalies of the eastern Pacific anticyclone and the subtropical high-pressure belt, the author shows that corresponding to the equatorward component of the tide-producing force of the Moon there is a similar variation in the parameters mentioned above.

Small semi-diurnal lunar tides in the atmosphere have been demonstrated by CHAPMAN [1939] and others, and are frequently mentioned in the literature, but observations of the longer period tides are lacking. In order to eliminate non-periodic variations and variations due to other periods from the pressure at Greenwich, Chapman used nearly two-thirds of a century of data. Since the longer period lunar tides are of smaller amplitude a much longer series of observations should be used. In fact to encompass a comparable number of cycles in the data several thousand years of observations would be necessary. Since no such record is available, we must turn to some element other than the pressure at a point to demonstrate the existence of such a tide in the atmosphere.

One possibility is the latitude of the subtropical anticyclones, since the horizontal forces at the high centers are small or else nearly balanced by other forces. Thus the small equatorward component of the lunar tidal force, acting over a number of days, may give rise to measurable displacements of the anticyclones.

As a test of this hypothesis, the latitude of the eastern Pacific anticyclone was tabulated for each day of the period May-August on which the High was clearly defined and on which there were no fronts within ten degrees latitude radius from the center. The latitude of the High was taken to be the latitude of the center of the cross-bar of the "H" as drawn on the maps, thus eliminating any subjectivity on the part of the tabulator. The tabulation was carried out for the last 20 years of data contained in the United States Weather Bureau Northern Hemisphere Historical Series of weather maps. From this tabulation the summer portion of the annual march of latitude was computed, and the latitude of the High expressed in terms of anomaly from this normal latitude for the day of the season. The 20-year average latitude anomaly for each day of the lunar bi-fortnightly cycle of declination is compared with the equatorward component of the tidal force in Figure 1. No explanation is offered for the apparently harmonic residue.

As a check on these results, the latitude of maximum pressure on the five-day mean north-south sea-level pressure profile averaged over 180 degrees of longitude was treated in the same manner. The resulting curve (see Fig. 2) is very similar to that obtained for the eastern Pacific High except for the period of the residue.

Dividing the data of Figure 1 into latitude classes it is seen that the phase lag of the High behind the tidal force varies roughly with latitude, as shown in Table 1.

Table 1--Variation with latitude of the lag of the eastern Pacific anticyclone behind the lunar force

Degrees	Days
43	3
40	4
37.5	7
35	5
32.5	8
30	9.5

This variation of phase angle makes a complete analysis of variance very difficult. Simplifying the problem by assuming a phase lag of six days, and of course reducing the statistical rigor thereby, an equation of estimation may be written

$$L_{d,c} = \bar{L}_d + a\,[\cos 2\pi/28\ (c - 6) + 0.7 \cos 4\pi/28\ (c - 6)]$$

where $L_{d,c}$ is the estimated latitude on day d of the year and c of the lunar cycle, and $\bar{L}_d$ is the mean latitude on day d of the year. The resulting analysis of variance based on this equation is presented as Table 2. Assuming complete independence of successive data, the level of significance reached is about one in a thousand. Since complete independence does not exist in meteorological data the level of significance is not as impressive, but still suggests that the presence of a lunar bi-fortnightly tide in the atmosphere is real.

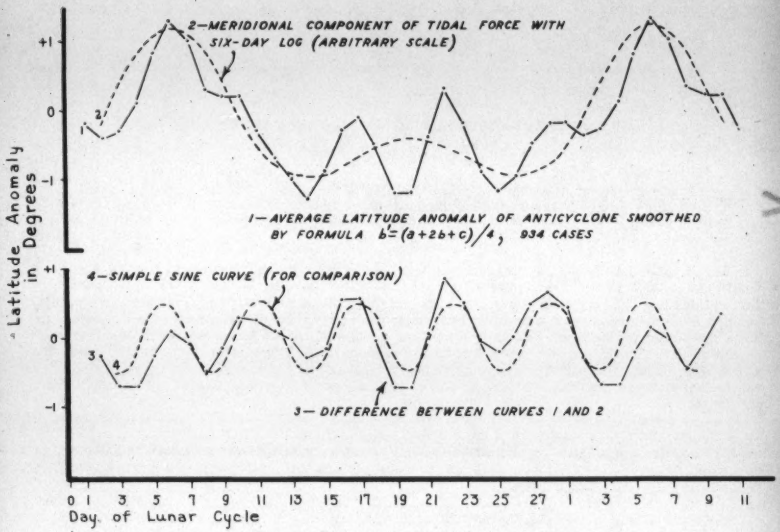
2—MERIDIONAL COMPONENT OF TIDAL FORCE WITH SIX-DAY LOG (ARBITRARY SCALE)
1—AVERAGE LATITUDE ANOMALY OF ANTICYCLONE SMOOTHED BY FORMULA b'=(a+2b+c)/4, 934 CASES
4—SIMPLE SINE CURVE (FOR COMPARISON)
3—DIFFERENCE BETWEEN CURVES 1 AND 2
Latitude Anomaly in Degrees
+1
0
-1
0 1 3 5 7 9 11 13 15 17 19 21 23 25 27 1 3 5 7 9 11
Day of Lunar Cycle

Fig. 1--Comparison of observed latitude anomaly of eastern Pacific anticyclone with meridional component of lunar tidal force (component depending on declination only), May-August 1919-1939

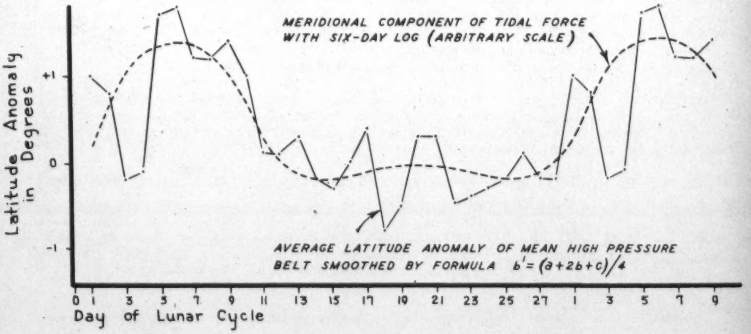
MERIDIONAL COMPONENT OF TIDAL FORCE WITH SIX-DAY LOG (ARBITRARY SCALE)
AVERAGE LATITUDE ANOMALY OF MEAN HIGH PRESSURE BELT SMOOTHED BY FORMULA b'=(a+2b+c)/4
Latitude Anomaly in Degrees
+1
0
-1
0 1 3 5 7 9 11 13 15 17 19 21 23 25 27 1 3 5 7 9
Day of Lunar Cycle

Fig. 2--Comparison of observed latitude anomaly of mean subtropical high-pressure belt with meridional tidal component, January 1944-April 1946

Table 2--Analysis of variance[a]

Source	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Probability
Annual mean latitude	122	....	....	...	....
Regression on lunar force[a]	1	256.7	256.7	11.1	~ 0.0014
Deviations from regression	822	19055	23.2	...	....
Total	945	....	....	...	....

[a]Six-day lag assumed.

Acknowledgments--The writer acknowledges the assistance of Mrs. Y. T. Wei in the tabulation of the data, and the United States Weather Bureau in supplying the five-day mean data and setting up the statistical tests.

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A MODIFIED WILD-PATTERN EARTH-INDUCTOR INCLINOMETER

William E. Wiles

Introduction--In the spring of 1946, the Division of Geomagnetism and Seismology of the United States Coast and Geodetic Survey undertook the planning of a new type of observatory earth inductor. Most of the planning and general supervision of the work was accomplished by Fred Keller, Jr., of the Division, the major part of the drafting being done by A. K. Howerter of the Division of Charts. All of the construction work was done by the United States Naval Observatory. Two new earth inductors were built, No. 7 and No. 8. After preliminary tests and observations indicated the acceptability of the instruments, it was decided to ship No. 7 to the San Juan Magnetic Observatory, to serve as the permanent, absolute instrument of the Observatory, replacing the one in use, and to retain No. 8 for use as a model in the construction of additional earth inductors. The eventual plan was to replace the old earth inductors in use at all of the observatories of the Bureau with the new, modified, improved type.

Design and construction--The new instrument may be termed a modified Wild-pattern earth inductor in that it comprises the basic principles of the Wild design employing commutator and large base ring but obtains coil rotation by means of a horizontal drive shaft activating the rotation axis of the coil through the medium of two quarter-sphere bevel gears. The coil is rotated by means of a flexible shaft and hand crank. The new inclimometer differs from the type in present use in the observatories of the United States Coast and Geodetic Survey chiefly in two respects: First, the dimensions of the base ring have been increased to improve the stability of the instrument and, second, coil rotation is effected indirectly from the side of the instrument through gears rather than directly from one of the ends of the coil axis, in order to reduce vibration and to eliminate any strain on the coil caused by the weight of the driving cable. A general view of this instrument is shown in Figure 1.

The horizontal circle for use in orientation is engraved on a fixed tripod ring, 25 cm outside diameter, supported by encased foot screws. The circle is graduated clockwise from 0° to 360° with 0° centered over one foot screw and with least count 30′. This can be easily read to one minute by means of two verniers, 180° apart, attached to the inner horizontal base ring. A gear allows for convenient slow motion setting of the inner ring. The supports for the alidade and horizontal drive shaft rest on and move with the inner ring. The coil is attached to a large gimbal and rotates on conical glass bearings. The bearing at one end of the coil axis is set in a sliding brass cup and at the other end in a centering brass cup adjustable by means of four capstan screws. Induction is obtained by two concentric coils of 900 turns each, mean diameter 10.2 cm, and total resistance about 120 ohms. Small changes in the inclination of the coil can be obtained by a tangent screw acting through a lever arm on the gimbal ring. To obtain verticality of the axis of the coil an adjustable level of sensitivity 10 to 15 sec per division is centered in the coil. Leveling of the inclination axis is derived through a ten-sec standard level set by dowel pins in a stride attachment resting on the ends of the axis of the gimbal ring. The orienting box compass also rests in this stride attachment. The vertical circle, 16.5 cm in diameter, with least count 20 min, is attached to the rotating horizontal extension of the gimbal ring. Two fixed, frame-supported verniers, with least count 20 sec, are read directly by two Ramsden eyepieces.

The instrument was constructed of carefully tested non-magnetic materials. The larger parts such as the base ring, upright supports, and gimbal ring were made of cast bronze in order to increase the total weight of the instrument for greater stability. A few parts such as the coil form were made of duralumin. The vertical circle consists of an inset silver band in a bronze ring.

Performance--After preliminary inspection and observations, complete standardization observations were made with earth conductor No. 7 at the Cheltenham Magnetic Observatory. Following this the instrument was sent to the San Juan Magnetic Observatory to replace the earth inductor in use. Earth inductor No. 8 was brought to the Tucson Magnetic Observatory and returned, standardization observations being made at Cheltenham before and after the trip. All of the standardization observations at Cheltenham and at Tucson were made by the writer. Observations of earth inductor No. 7 at San Juan have been made only by Observatory personnel. Table 1

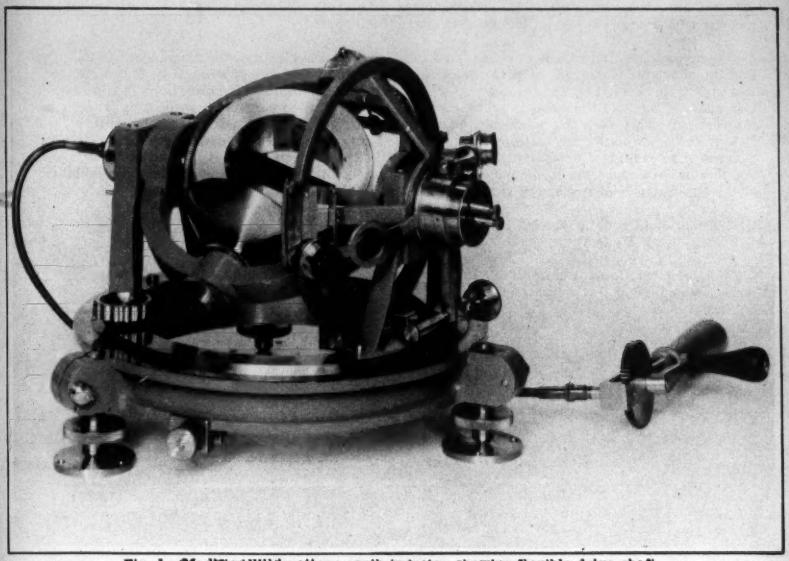

Fig. 1--Modified Wild-pattern earth inductor showing flexible drive shaft

Table 1--Comparison of earth inductors

Date	Place	Instrument No.	No. of sets	Differences		Ranges
				Comparison with	Value	
1947						
Dec. 1, 2	Cheltenham	7	12	48 and 7	-0.1	0.4
1948						
Jan. 20, 21	Cheltenham	7[a]	12[b]	48 and 7	+0.1	0.5
Feb. 4, 5, 6	San Juan	7	14			0.4
Jan. 22, 27	Cheltenham	8	16[b]	48 and 8	+0.8	0.5
Feb. 11, 12	Tucson	8	9[b]			0.4
Feb. 26, 27	Cheltenham	8	9[b]	48 and 8	+0.2	0.3

[a]Instrument adjusted in shop between December 2 and January 20.

[b]Observations made on different foot screws; in the other cases the observations were made on one foot screw. The results of observations made on different foot screws indicated that the new earth inductors were entirely non-magnetic.

summarizes the observations made with both new earth inductors, and shows the mean observed differences between the new instruments and the standard earth inductor, No. 48 (Carnegie Institution of Washington), at Cheltenham. In all cases the comparison was derived through the magnetograph. Pier-difference corrections were unnecessary since all observations with the new earth inductors were made on the same pier as that regularly used for earth inductor No. 48. The ranges shown are the ranges in the differences obtained by comparing the observed values of inclination with the values derived through the Observatory magnetograph.

The ranges obtained were consistent and agreed closely with the ranges obtained from the regular Observatory dip observations made during the period.

Conclusions--The ranges of observed differences obtained through the magnetograph indicated that the new type of instrument gave results of about an equal degree of reliability as the old type. It was felt, however, that improved accuracy would result from slight modifications in construction plans. Thus, it is planned to substitute brass in place of the duralumin supporting frame for the vertical circle verniers in order to increase rigidity and hence stability of the instrument, and to have the lines on the vertical circle and verniers engraved thinner in order to improve ease and accuracy of readings. It was generally considered that the changes in design were basically sound and that the new type represented an improvement on the old type, especially as regards stability of the instrument and absence of vibration and strain on the rotating coil.

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CHARACTERISTICS FOR SOME ALLOY MAGNETS FOR GEOMAGNETIC INSTRUMENTS

Roland F. White

One method of magnetic observation employed by the United States Coast and Geodetic Survey is one which determines both horizontal intensity and the moment of the magnetometer magnet. Thus as long as the magnet retains a constant moment the results give a check on the accuracy of the field observations. With good observations the computed value of the moment will not change with changing values of intensity.

There are two properties of the magnet which must be known in computing the results of observations. These are the temperature coefficient and the induction factors. Magnets normally lose moment as the temperature increases. This change is not linear but for the temperatures at which observations are normally obtained it can be considered so without serious error. The moment of a magnet is also changed by induction by the field of any other magnet and by the Earth's field. The moment of a magnet at any temperature in an ambient field is expressed by

$$M = M_0[1 + (t_0 - t)q][1 + \mu H/M_0]$$

in which M_0 is the moment of the magnet at standard temperature, t_0 and zero ambient field; t, the temperature; q, the temperature coefficient; μ, the induction factor. and H, the component of the ambient magnetic field parallel with the axis of the magnet.

Temperature coefficient is measured by determining the moment of the magnet at different temperatures. This is done by surrounding the magnet with a water bath and making deflection observations at controlled temperatures. For the computation, horizontal intensity at the times of observations is obtained from the observatory records.

The induction factor is determined by the method developed by NELSON [1938] of the Coast and Geodetic Survey. The method consists, basically, of mounting two solenoids, one on each side of a magnetometer with axes vertical. The two coils are connected in series and they are so placed that their fields balance and do not deflect the suspended magnet. The test magnet is placed within one of the solenoids with axis vertical. Deflections are observed with current through the coils direct, reversed, and off. The variations in deflections are a measure of the induction coefficient.

Table 1--Moments, temperature coefficients, and induction factors of magnets

Magnet type and size	Moment M	Temperature coefficient q	Induction factor μ
	cgs units	per °C	cc
Tungsten steel, No. 31LT, 0.7× 9.28 cm	1112	0.000365	8.5
36 per cent cobalt steel, No. 31LC, 0.7× 9.28 cm	2660	0.00018	3.5
Alnico II, 0.7 × 9.28 cm	1240	0.00028	1.02
Alnico VI, No. 6A, 0.635 × 7.62 cm	1712	0.00024	0.52

Table 1 gives the results of tests on properties of magnets made over a period of several years. For the first three magnets, the tests were made in connection with standardization of magnetometers. The tests on the Alnico VI magnet were made in standardizing a number of magnets for the W. and L. E. Gurley Company, who will use them as standards in building and testing magnetometers and compasses.

The moments given are for particular magnets of the various materials and are not necessarily the maxima possible for these materials.

As can be seen from the table, cobalt steel has a smaller temperature coefficient and smaller induction factor than tungsten steel. It is also capable of being more strongly magnetized. Alnico II has a larger temperature coefficient but a considerably smaller induction factor than cobalt steel; it can retain a greater moment than cobalt steel. Alnico VI has a temperature coefficient not much different from Alnico II but its induction factor is about one-half that of Alnico II. We do not have data on its ability to retain a large moment.

For our purpose, low temperature coefficient and induction factor are important. As long as the moment remains constant or nearly so over a period of years it does not have to be large.

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U. S. Coast and Geodetic Survey,
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DIFFRACTION OF WATER WAVES BY BREAKWATERS

J. A. Putnam and R. S. Arthur

(Contribution from the University of California, Fluid Mechanics Laboratory Publication No. HE-116-280, and the Scripps Institution of Oceanography, New Series, No. 371)

Abstract--Application is made of a solution of the water-wave diffraction problem of Penny and Price to diffraction by a semi-infinite impermeable breakwater. Approximations are introduced to simplify application of the theory. Comparison of complete and simplified solutions is made with results obtained from a laboratory investigation. Best agreement between theory and experiment occurred in the lee of the breakwater. The simplified solution is shown to be adequate for most practical applications.

Introduction

Wave diffraction is considered here to be the phenomenon in which water waves are propagated into a sheltered region formed by a breakwater or similar barrier which interrupts a portion of an otherwise regular wave train. A knowledge of diffraction behavior has important application in the design and location of breakwaters in connection with harbor development. It would also appear to have a bearing on the distribution of wave energy along beaches located in the lee of headlands and offshore islands.

The sheltering effect of a breakwater of finite length and vertical impermeable walls depends upon diffraction of the incident waves around the ends of the breakwater. The phenomenon is quite analogous to the diffraction of light and a theory of breakwater diffraction has been adapted from the theory of physical optics. This paper presents a review of the theory and comparison is made with the results of experiments which were carried out with a view toward confirmation of this theory.

Theory

PENNY and PRICE [1944] have shown that Sommerfeld's solution of the optical diffraction problem [BATEMAN, 1944, pp. 476-485] is also a solution of the water-wave diffraction problem. The following discussion deals with a form of the solution which is modified from the original, and which appears to be particularly adapted to the present application.

Solution for progressive waves without a barrier present--A treatment of progressive waves is given in considerable detail by LAMB [1932, pp. 363-369]. Assume a cylindrical co-ordinate system with r and θ in the plane of the undisturbed water surface as shown in Figure 1, and the z-axis vertically upwards. Let η be the elevation at time t of the water surface above the undisturbed level.

The following assumptions are made regarding the wave motion and the boundary conditions: (1) The motion is irrotational and the velocity potential therefore satisfies Laplace's equation; (2) the motion is infinitely small; (3) at a fixed boundary the normal component of the fluid velocity is zero; (4) at the free surface the pressure is constant; and (5) the water is of uniform depth h.

Under these assumptions the expression for the surface elevation is of the form

$$\eta = (AikC/g)e^{ikCt} \cosh kh \cdot F(r, \theta) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $i = \sqrt{-1}$ but only the real part is to be finally retained and where $F(r, \theta)$ satisfies the equation

$$(\partial^2 F/\partial r^2) + (1/r)(\partial F/\partial r) + (1/r^2)(\partial^2 F/\partial \theta^2) + k^2 F = 0 \quad \ldots\ldots\ldots\ldots (2)$$

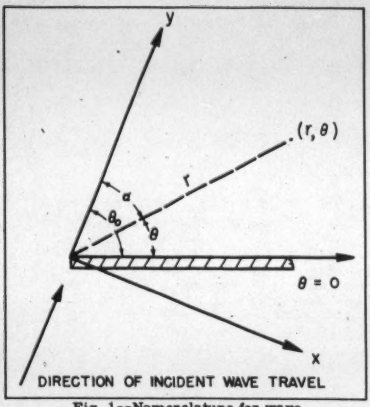

Fig. 1--Nomenclature for wave diffraction analysis

The meaning of the constants A, k, and C is best illustrated by considering the case of progressive waves traveling in the direction $\theta = \theta_0$ for which

$$F(r, \theta) = e^{-ikr \cos(\theta_0 - \theta)} \quad \ldots (3)$$

and the resulting waves have the following properties:

Length = $L = 2\pi/k$
Period = $T = 2\pi/kC$
Amplitude = $a = (AkC/g) \cosh kh$
Velocity = $C = \sqrt{(g/k) \tanh kh}$

Solution with a barrier present--The additional boundary condition imposed by the barrier must also be satisfied. Assume a barrier in the form of a rigid breakwater extending from the origin along the initial line $\theta = 0$.

To determine the nature of the diffracted waves it is necessary to obtain a solution of (2) for which the normal component of the fluid velocity is zero along the breakwater and which reduces to (3) for large values of r when $\theta = 180°$. Sommerfeld obtained such a solution for the diffraction of light by a semi-infinite screen in the case where the light is polarized in a plane parallel to the edge of the screen [BATEMAN, 1944, p. 484].

$$F(r, \theta) = (1/\sqrt{2})\, e^{i[(\pi/4) - kr \cos(\theta_0 - \theta)]} \int_{-\infty}^{u_1} e^{-i\pi v^2/2}\, dv + (1/\sqrt{2})\, e^{i[(\pi/4) - kr \cos(\theta_0 + \theta)]} \int_{-\infty}^{u_2} e^{-i\pi v^2/2}\, dv \quad \ldots (4)$$

where

$$u_1 = -\sqrt{4kr/\pi} \sin[(\theta_0 - \theta)/2] \text{ and } u_2 = -\sqrt{4kr/\pi} \sin[(\theta_0 + \theta)/2] \quad \ldots (5)$$

The dependence of the surface elevation η upon solution (4) can now be investigated. Since $F(r, \theta)$ is a complex number it can be written in the form

$$F(r, \theta) = \rho(r, \theta)\, e^{i\phi(r, \theta)} \quad \ldots (6)$$

where $\rho(r, \theta)$, the modulus of $F(r, \theta)$ is hereafter denoted by the symbol $|F(r, \theta)|$, and $\phi(r, \theta)$, the argument of $F(r, \theta)$, is hereafter denoted by arg $F(r, \theta)$. Substitution of (6) in (1) leads to the expression

$$\eta = (AkC/g) \cosh kh \cdot |F(r, \theta)|\, e^{i[(\pi/2) + kCt + \arg F(r, \theta)]} \quad \ldots (7)$$

where only the real part is to be retained. Equation (7) shows that the modulus of $F(r, \theta)$ determines the amplitude of the diffracted waves, and that the argument determines the wave pattern. A diffraction factor, K', is now defined to be the diffracted wave height divided by the incident wave height, in analogy to the refraction factor, K [MUNK and TRAYLOR, 1947]. From (1), (3), and (7)

$$K' = (2AkC/g) \cosh kh \cdot |F(r, \theta)| / [(2AkC/g) \cosh kh] = |F(r, \theta)| \quad \ldots (8)$$

Complete solution for $F(r, \theta)$--For the complete evaluation of $F(r, \theta)$ a function $f(u)$ is defined as

$$f(u) = (1/\sqrt{2})\, e^{i\pi/4} \int_{-\infty}^{u} e^{-i\pi v^2/2}\, dv \quad \ldots (9)$$

The modulus and argument of f(u) can be determined from tabulated values of the Fresnel integrals, C(u) and S(u) [JAHNKE and EMDE, 1943, pp. 34-36]; for $u>0$

$$C(u) - iS(u) = \int_0^u e^{-i\pi v^2/2}\, dv \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

For $u<0$, the relationship $f(-u) = 1 - f(u)$ which can be derived from (9) is useful. The modulus and argument of f(u) are represented graphically in Figure 2, and since the integrals in solution (4) can be expressed in terms of $f(u_1)$ and $f(u_2)$, a complete evaluation of $F(r, \theta)$ is possible. The labor involved in computations can be reduced by the introduction of approximations.

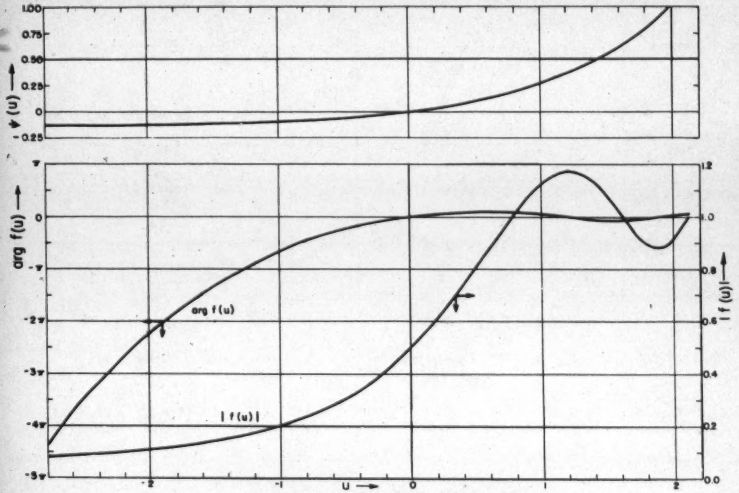

Fig. 2--Functions of u: $\Psi(u)$, arg f(u), and mod f(u)

For $u<-2$ it is possible to use the approximation [BATEMAN, 1944, p. 483]

$$f(u) \cong -(1/\pi\sqrt{2}\, u)\, e^{-i\pi[(1/4) + (u^2/2)]} \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The value of u_2 which occurs in (4) is less than -2 for the greater part of the region beyond the breakwater. After introduction of $f(u_1)$ and $f(u_2)$ for the integrals and approximation of $f(u_2)$ by (11), expression (4) can be written in the form

$$F(r, \theta) = \left\{ |f(u_1)| - (1/\pi\sqrt{2}\, u_2)\, e^{-2\pi i[(1/8) + \Psi(u_1)]} \right\} e^{-2\pi i[(r/L) - \Psi(u_1)]} \quad \ldots\ldots (12)$$

where (assuming $u_2 < -2$)

$$u_1 = -\sqrt{8r/L}\, \sin[(\theta_0 - \theta)/2]$$

$$u_2 = -\sqrt{8r/L}\, \sin[(\theta_0 + \theta)/2]$$

$$\Psi(u) = (u^2/4) + \left\{ [\arg f(u)]/2\pi \right\}$$

$\Psi(u)$ is represented graphically in Figure 2.

Evaluation of K' can be accomplished from (12), since it will be recalled that K' equals the modulus of $F(r, \theta)$ which in this case is the modulus of the first factor on the right-hand side of (12). This modulus is obtained graphically by representing each of the two terms in the first factor as vectors and combining vectorially. The argument when added to the argument of the second factor gives the argument of $F(r, \theta)$.

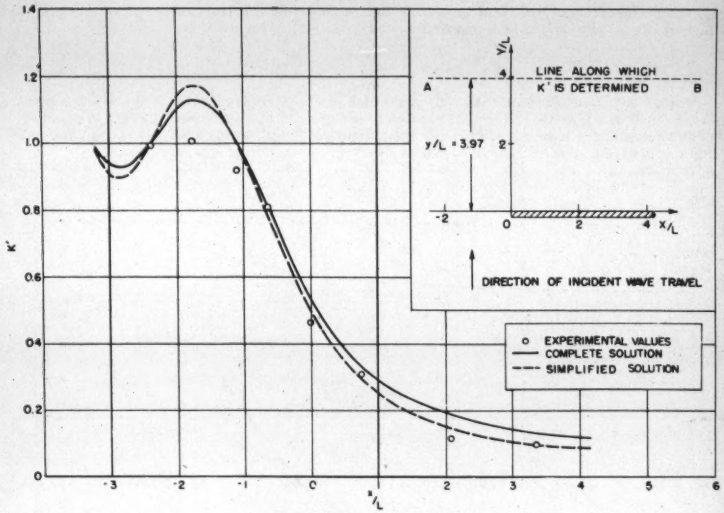

Fig. 3--Comparison of the simplified solution with the complete solution of the water-wave diffraction problem

In certain parts of the region beyond the breakwater, (12) can be further simplified to forms utilized in optical diffraction. The results for three such special cases follow:

Case 1: $u_1 = 0$, $(\theta = \theta_0)$

$$F(r, \theta) = [(1/2) - (1/\pi\sqrt{2}\, u_2)\, e^{-\pi i/4}]\, e^{-2\pi i r/L} \quad \ldots\ldots\ldots\ldots (13)$$

Case 2: $u_1 < -2$

$$F(r, \theta) = [-(1/\pi\sqrt{2}\, u_1) - (1/\pi\sqrt{2}\, u_2)]\, e^{-2\pi i[(r/L) + (1/8)]} \quad \ldots\ldots\ldots\ldots (14)$$

Case 3: $u_1 > 2$

$$F(r, \theta) = \left\{1 + (1/\pi\sqrt{2})\,[(1/u_1) + (1/u_2)]\, e^{-2\pi i\,[(u_1^2/4) - (3/8)]}\right\} e^{-2\pi i\,[(r/L) - (u_1^2/4)]} \quad \ldots\ldots (15)$$

The curve labeled "complete solution" in Figure 3 has been computed by use of these approximations when appropriate.

Simplified solution--The second term in the first factor of (12) can be completely neglected when its modulus is small compared to $|f(u_1)|$. However, this will not be the case if (r/L) is small, or if 2 is small as shown in Figure 3. If this simplification of ommitting the second term in (12) is introduced it is convenient to transform back to rectangular co-ordinates by means of the relationships $y = r \cos(\theta_0 - \theta)$ and $x^2 + y^2 = r^2$. The resulting expression can be written in the form

$$F(x, y) = e^{-2\pi i y/L} \cdot f(u_1) \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

where

$$u_1^2 = (4/L)\,(\sqrt{x^2 + y^2} - y) \quad \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

and the sign of u_1 is to be determined by reference to the expression for u_1 given in (5). The curve labeled "simplified solution" in Figure 3 has been computed by this method.

Barrier of finite length--No exact solution has been found for the case of a barrier of finite length. It is believed that satisfactory results can be obtained by using a solution of the type indicated above for each end of the barrier. The co-ordinate systems assigned to each end must be mirror images of each other. The waves diffracted from the two edges will produce an interference pattern beyond the barrier, and the maximum height of the waves may be assumed to be equal to the sum of the heights from the two trains.

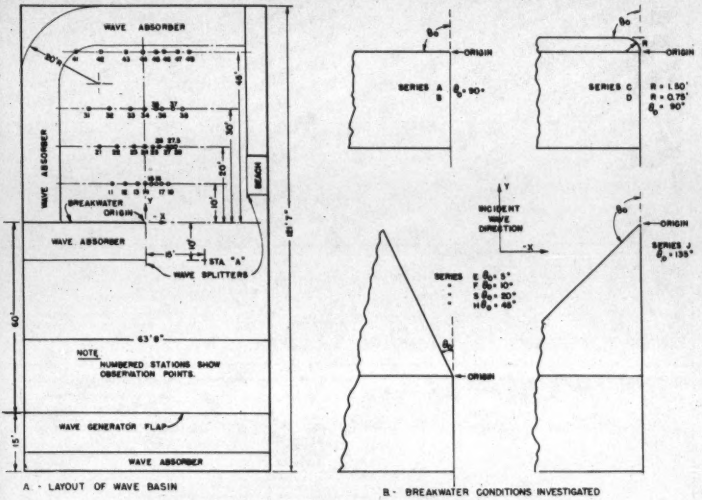

Fig. 4--Model basin arrangement for wave-diffraction studies; A, layout of wave basin; B, breakwater conditions investigated

Experiments

In order to test the validity of the foregoing theory of water-wave diffraction by a rigid breakwater, an experimental investigation was undertaken in the Fluid Mechanics Laboratory of the University of California, Berkeley. Measurements were restricted to only those required for the diffraction coefficient and not for crest lag.

Wave-basin arrangements--The experimental arrangement is shown in Figure 4. All vertical surfaces which would cause reflection of waves were provided with wave absorbers which consisted of gradually sloping rough beaches. The arrangement shown in Figure 4A is for the breakwater aligned at 90° to the direction of incident-wave propagation ($\theta_0 = 90°$). The numbered stations represent the location of wave-height recorders for all runs. The effect of angle of wave incidence was also investigated by arranging the breakwater as shown in Figure 4B. Moreover, for $\theta_0 = 90°$, additional studies were made for a breakwater with rounded tip for two radii as shown in Figure 4B.

The depth of fresh water in the basin being restricted to 1.5 ft, the maximum wave period for deep-water conditions was 0.76 sec. The minimum period that could be used safely was governed largely by harmonics of the natural period of oscillation of the wave basin and by the stability of the waves at the instant of leaving the wave generator. Accordingly, the lowest wave period used was 0.70 sec. Only one wave period is theoretically required to check the diffraction theory. However, investigation with a second wave period served to check the first results.

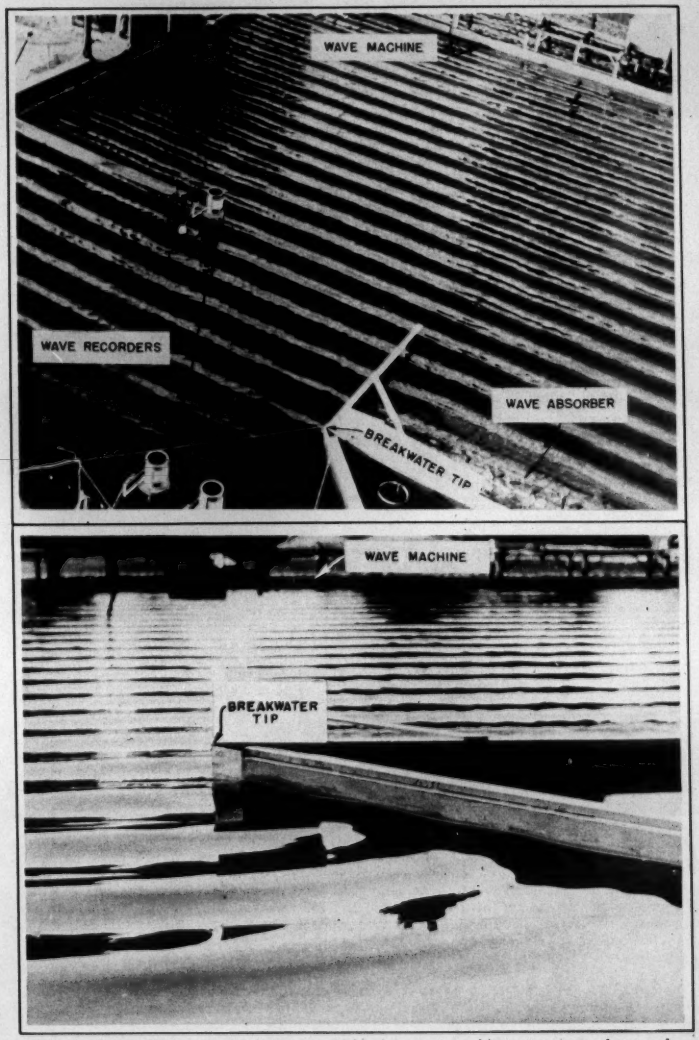

Fig. 5--Views of experimental equipment showing wave machine, wave recorders, and effect of diffraction for a breakwater at 45 degrees to the incident wave (wave period = 0.70 sec)

Waves of constant amplitude and period were generated by means of a flap which was hinged at the bottom of the basin and made to rock back and forth with a crank mechanism driven by a direct current motor.

Wave-height measurements--Wave heights were measured with float-type recorders as shown in Figure 5, which had been calibrated by direct comparison with electrical point-gage measurements of the same group of waves that was recorded on the float gages during the calibration runs. A series of carefully controlled experiments was made in order to estimate the accuracy of the wave-height measurements as influenced by accidental variations in incident-wave height, effect of small wind gusts, and instrument response. The results indicated that the wave heights were determined with a probable error of ± 12 per cent. By use of electrical resistance or capacity recording gages or pressure-sensitive recording gages and by enclosing the wave basin to avoid the effect of air disturbances, the accuracy of wave-height measurements could be improved.

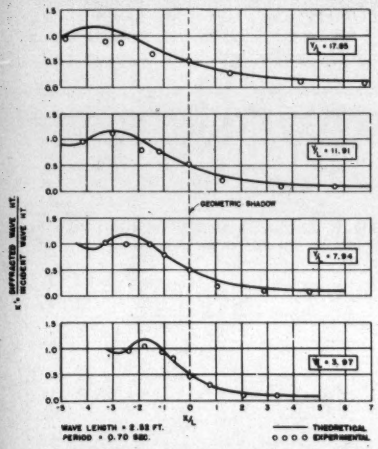

Fig. 6--Diffraction coefficients with breakwater at 90° to incident waves

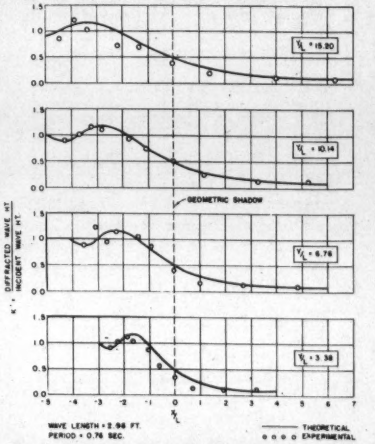

Fig. 7--Diffraction coefficients with breakwater at 90° to incident waves

Experimental procedure--Six wave-height recorders were available for the studies. For each run, one wave recorder always was operated at Station A (see Figs. 4 and 5) in order to obtain the height of the incident waves. The other five recorders were operated at selected stations in the lee of the breakwater. Approximately four runs were made for each set of five stations until the entire area beyond the breakwater had been covered. Wave periods were obtained by counting strokes of the wave generator during one-minute intervals at the beginning and end of each run. Wave periods could be reproduced very easily with probable errors less than one-tenth per cent. The average value of the ratio of wave height to wave length in deep water was approximately equal to 0.035 which closely approximates waves of small amplitude.

Experimental results--The averaged experimental results are plotted in Figures 6 to 11 covering the entire range of experiments. Theoretical curves based on the simplified solution expressed by (16) and (17) are also shown. The breakwater tip is at the origin of coordinates and extends in the positive x-direction. The quantity used for comparison is the diffraction factor K' = diffracted wave height/incident wave height.

Comparison of experiment with theory

The diffraction theory is applicable to all angles of incidence and wave periods but is not intended to apply to other than sharp-cornered breakwater tips. The theory also assumes a semi-infinite breakwater of negligible thickness, and wave crests extending to infinity in both directions.

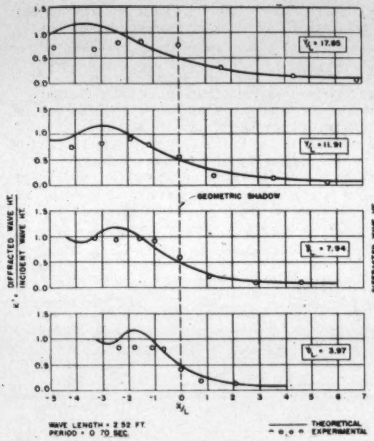

Fig. 8--Diffraction coefficients with breakwater at 45° to incident waves

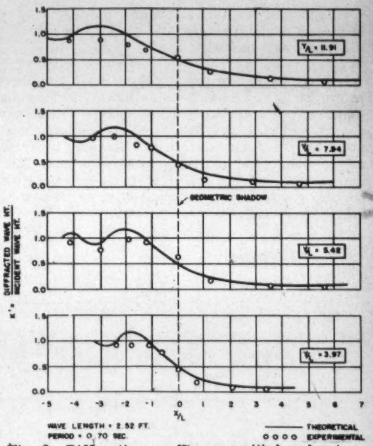

Fig. 9--Diffraction coefficients with breakwater at 135° to incident waves

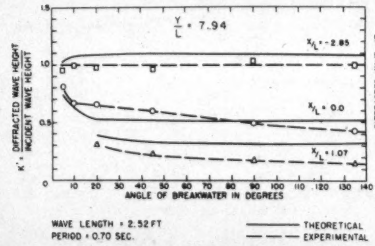

Fig. 10--Effect of angle of breakwater on the diffraction coefficient

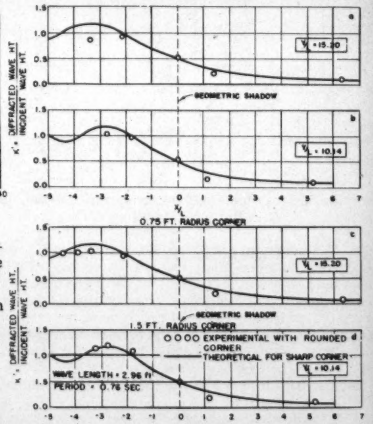

Fig. 11--Diffraction coefficients with rounded breakwater tips

Referring to Figures 6 and 7, it can be seen that wave period had little effect on the diffraction behavior. In general, the agreement with the simplified solution is remarkably good in the lee of the breakwater, even for short distances to leeward where it might be expected that the complete solution should give better agreement. Inspection of Figure 3 indicates that the complete solution for $y/L = 3.97$ yields values of K′ somewhat in excess of both the simplified solution and the experimental values. The nature of the term omitted in the derivation of the simplified solution is such that the difference between the complete and simplified solutions increases from approximately zero at $y/L = 10$ to a maximum at $y/L = 0$. The agreement of the experimental results with the simplified solution, rather than with the complete solution, may be due to the finite thickness of the experimental breakwater. However, this explanation cannot be definitely established since there are not sufficient experimental data for smaller values of y/L. In the unprotected region, outside the geometric shadow, larger differences occur between experiment and theory. The actual wave heights are generally smaller than heights predicted by theory although the deviations are

within the order of magnitude of the experimental errors. If the theoretical diffraction curves were to be used for breakwater-design purposes, results would be conservative in that the actual wave heights would tend to be somewhat less than predicted values.

The results presented in Figures 8 and 9 are for waves of period 0.70 sec period and for breakwater directions of 45° and 135°, respectively. Again the agreement between theory and experiment is reasonably good in the protected region. However, in the unprotected region the difference becomes quite large, with the experimental wave heights generally being considerably smaller than the theoretical heights. In these two figures the breakwater tip is at the origin of coordinates, but the breakwater itself extends toward the right of the geometric shadow and at the appropriate angle.

Values of K′ have been plotted against breakwater angle for various values of x/L and a value of y/L = 7.94 in Figure 10. Comparison is made with theoretical values based, in this case, on the complete solution. For x/L = -2.85 (outside the geometric shadow) the diffraction coefficients obtained experimentally are approximately 18 per cent less than the theoretical value of K′ = 1.18. At the geometric shadow (x/L = 0) the experimental value agrees with the theoretical value of a breakwater angle of 90°. With increasing breakwater angle the experimental values are less than the theoretical values. For angles less than 90° the experimental values are larger than the theoretical, reaching a maximum deviation at 20°. The same behavior occurs in the lee of the breakwater (x/L = 1.07) except that the experimental results all fall below the theoretical values.

The results presented in Figure 11 were obtained for breakwater tips with rounded ends. Evidently the geometrical shape of the breakwater tip, within the limits of this investigation, has no material influence on the wave-diffraction pattern. With the sharp corner it was observed that a secondary disturbance originated at the corner which propagated capillary waves with a circular pattern superposed upon the main gravity-wave system. Rounding of the corners eliminated all such secondary capillary-wave systems. The finite thickness of the breakwater may account for many of the discrepancies between the observed diffraction behavior and the theoretical behavior which assumes a breakwater of negligible thickness.

In this investigation no attempt was made to compare theoretical crest lags with experimental values. Crest lag is of secondary importance in most harbor design. However, it is of importance where beach erosion may take place on enclosed beaches as at Long Beach, California, or on seacoast beaches in the lee of offshore islands or projecting headlands. In this connection, crest lag becomes of importance in determining wave direction and refraction diagrams. Experiments currently underway in the Fluid Mechanics Laboratory include measurements of crest lag in connection with an investigation of diffraction by gaps in breakwaters.

Conclusions

Although the accuracy with which the diffraction coefficients could be determined experimentally is not all that might be desired, it is possible to make the following conclusions:

(1) The experimental results verify the general form of the wave-diffraction theory.

(2) Best agreement was obtained for the region sheltered by the breakwater for all angles of incidence investigated. In the region close behind the breakwater the experimental values agree almost perfectly with the simplified theoretical solution. The complete solution yields diffraction coefficients in this region which are too large compared to the experimental values.

(3) At increasing values of y/L the simplified solution approaches the complete solution so that the former, which is less complicated, may be applied safely for all values of y/L.

(4) Outside the geometric shadow the experimental wave heights were, in general, considerably less than the theoretical heights.

(5) In all cases investigated the effect of wave period was negligible.

(6) Within the limits of the experimental conditions no effect on diffraction resulted from rounding off the tip of the breakwater.

(7) The simplified theoretical solution may be applied to the location and design of breakwaters with conservative results. In other words, the predicted wave heights in disturbed regions in the lee of the breakwater will be somewhat larger than the height of waves that may be expected in nature.

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CONSTANCY OF TEMPERATURES AT FISH SPRINGS, UTAH

Ronald L. Ives

Comparison of recently recorded temperatures at Fish Springs, Tooele County, Utah, with a series of measurements made by GILBERT [1928, pp. 72-73 and pl. 31; IVES, 1946] in 1879, discloses that neither individual springs nor the group of thermal springs as a whole have changed temperature significantly during the elapsed 65 years.

Noted temperatures of individual springs, in °F, are shown in Table 1.

Table 1--Temperature of waters at Fish Springs, Utah

Spring	1879	1945
	°F	°F
1	104.5	107
2	136.5	138
3	a	88
4	139	140
5	99	97
6	137	136
Average	123.2	123.6[b]

[a]Too muddy to approach in 1879; mud still present in 1945; two additional springs were noted, but not measured, by Gilbert in 1879; one of these had a temperature of 140° in 1945; the other was inaccessible. [b]Spring 3 omitted.

In view of this long-term constancy, it appears that changes in spring temperatures reported to Gilbert in 1901, and to the writer in 1945, by local residents, are either short-lived and self-compensating, or are the result of mistaken observations.

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THE NATURAL AND ARTIFICIAL FORMATION OF SNOW IN THE ATMOSPHERE

Vincent J. Schaefer

Abstract--Experiments, both in a laboratory and in nature, are described, in which small quantities of solid carbon dioxide have been used to produce enormous quantities of snow crystals from clouds of supercooled water droplets. The solid carbon dioxide, or any other object colder than about -39°C, converts the supercooled water droplets to tiny ice crystals which grow, by vapor exchange, and become snow crystals. The conditions under which such action may be followed by precipitation are discussed.

The occurrence of snow storms in temperate regions constitutes a natural phenomenon which affects the lives and interests of a large segment of the world's population. In fact, even in semi-tropical countries, the presence or lack of ice nuclei in the subfreezing levels of high cumulus clouds probably determines to a considerable extent the amount of rain, the occurence of hail, and the intensity of subsequent storms developing from such cloud structures.

For many years experiments have been conducted in laboratories throughout the world studying various aspects of snow, both in the laboratory and the atmosphere. In fact, there are so many that it is impossible to include more than a few references to the work of typical workers in the field [ADAMS, 1930; BARNES, 1929; BERGERON, 1933; WEGENER and WEGENER, 1935; FINDEISEN and SCHULZ, 1944; NAKAY, TODA, and MARUYAMA, 1938; WEICKMANN].

Recently a simple method was described [SCHAEFER, 1946 a and b] for producing tremendous quantities of ice nuclei in supercooled clouds. By introducing moist air into a cold chamber 30 cm × 50 cm × 50 cm deep, having a temperature of -20°C at the bottom and -8°C at the top, a supercooled cloud may be formed identical in physical characteristics, such as liquid water content and droplet size, to many subfreezing clouds which occur in the natural atmosphere. Due to the temperature inversion in the chamber, it is possible to conduct many experiments with the top removed. It was shown that a tiny fragment of dry ice passed momentarily through such a cloud would produce enormous quantities of submicroscopic ice nuclei which would grow at the expense of the supercooled water droplets into small snow crystals. Such crystals are identical with those which form in the natural atmosphere and a typical sample of the crystals is shown in Figure 1. It was also reported than any object colder than minus 35°C when introduced into a supercooled cloud of water droplets would innoculate the region with ice nuclei. Subsequent experiments indicate that this temperature is more likely about -39°C.

The suggestion was made that it should be possible to modify supercooled clouds in the natural atmosphere by seeding them with fragments of dry ice. The first such experiment in the natural atmosphere was carried out by the writer on November 13, 1946, when, in a small Fairchild cabin plane piloted by C. G. Talbot, a four mile stratocumulus cloud was seeded with granulated dry ice at the rate of 1 1/2 pounds per mile. Half of this was fed from a simple dispensing mechanism in the floor of the plane, the other portion being distributed by having the slip stream at the open window suck the dry ice fragments from the open end of cardboard mailing tubes.

The entire cloud, which had a temperature of -18.5°C at an altitude of 14,000 ft, was transformed to snow within a few minutes with long streamers of crystals falling below the cloud for a period of nearly an hour.

This initial experiment and subsequent successful ones by the writer and others [KRAUS and SQUIRES, 1947; ELLISON, 1947] have demonstrated the feasibility of causing large scale effects in supercooled clouds of the natural atmosphere. As often happens, however, when scientific experiments are widely publicized, certain erroneous conclusions are drawn due to lack of details.

It is a common observation in many parts of the world that the formation of snow does not necessarily occur when a cloud reaches a temperature slightly below the freezing point. Within recent years the most intensive studies of supercooled clouds have been carried out at the Mt. Washington Observatory in New Hampshire. The research on Mt. Washington has been directed primarily toward a better understanding of the basic physical facts related to the formation of ice

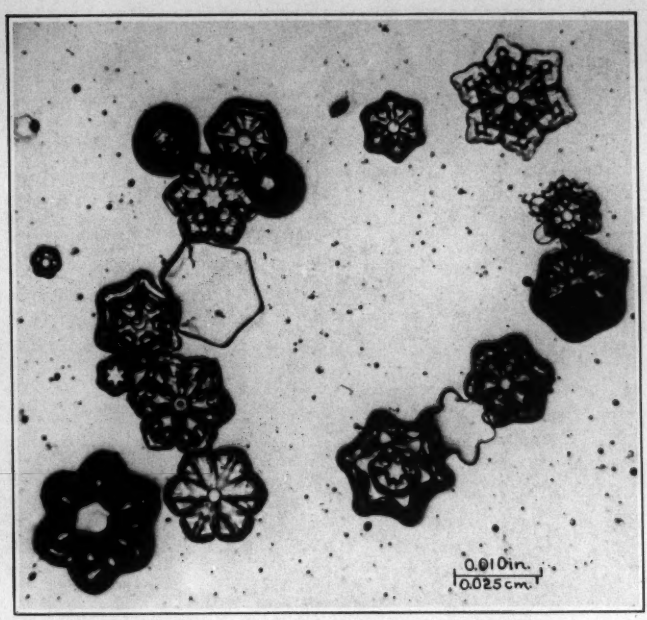

Fig. 1--Typical crystals formed in cold chamber by seeding

on air foils and other surfaces, from supercooled clouds. Many interesting facts have been determined in these studies, some of which have been described in bulletins [MT. WASHINGTON OBSERVATORY, 1945-1946] and reports [SCHAEFER, 1946; ANNONYMOUS, 1946] by members of the Observatory and our laboratory.

On the mountain most of the storms that sweep over the summit between October and June are accompanied by icing from supercooled clouds. A typical condition following such a storm is illustrated in Figure 2. All of this ice deposit which grows into the wind is formed from supercooled clouds. Icing has been observed at temperatures as low as -38°C.

Sometimes when the summit becomes clear of clouds, a lower layer of clouds still in a supercooled condition may be seen as shown in Figure 3. Such clouds commonly exist without showing a trace of ice crystals.

At other times, however, copious amounts of snow form and fall continuously from clouds nearly identical in thickness and temperature. Such a case is illustrated in Figure 4.

The existence of supercooled clouds in the natural atmosphere in addition to being of scientific interest has become of increasing economic importance with the increase in airplane traffic. When serious icing is expected, flight plans are commonly cancelled. When such conditions suddenly develop in the vicinity of an important airport, serious congestion, much inconvenience, and monetary loss often occurs.

If any appreciable precipitation is to result from seeding activities in clouds which show no tendencies to develop precipitation, certain basic factors must be present:

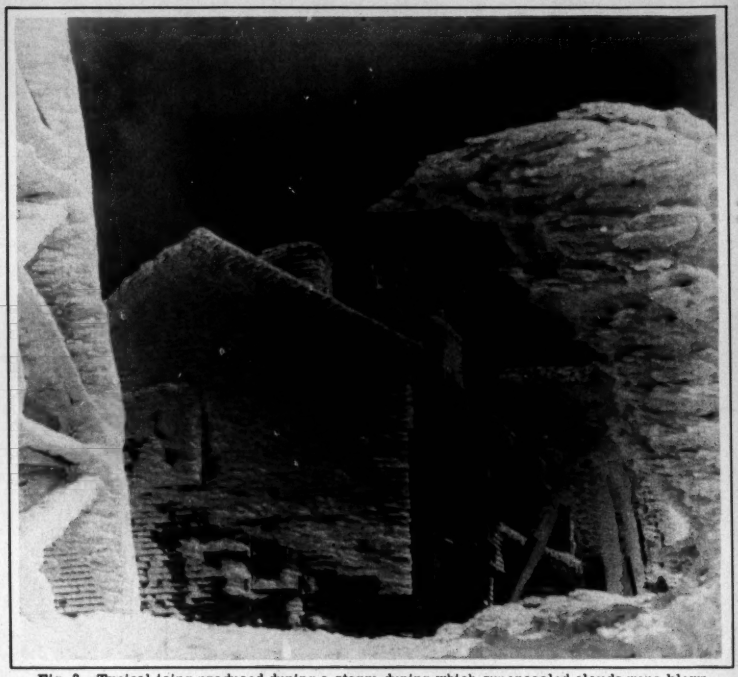

Fig. 2--Typical icing produced during a storm during which supercooled clouds were blown over the summit with the winds of hurricane force

(1) The temperature of the cloud must be colder than 0°C (32°F).

(2) Besides being colder than the freezing point, the cloud must consist of liquid water droplets which are in a supercooled state. This supercooled region must have appreciable thickness with at least 500 ft colder than 0°C.

(3) The cloud area to be modified must have sufficient vertical development in the supercooled region that the snow particles grow to a sufficient size to continue falling when they enter the region above the freezing point.

(4) If most of the cloud has a temperature above freezing, there must be available moisture below the supercooled region to sustain the growth of the melted snow particles so that their falling velocity exceeds the upward velocity of air within the cloud. With sufficient falling velocity, the particles will continue to grow in the warmer part of the cloud by coalescence with cloud droplets intercepted, and by condensation of water vapor on these particles by virtue of their lower temperature and vapor pressure.

(5) If the precipitation is to reach the ground, the air below the cloud must contain enough moisture that the particles do not evaporate before reaching the ground.

(6) The amount of convergence and uplift of moist air in the affected region will exert a major influence on the duration of the seeding effect. If this condition is favorable for the evolution of

fresh condensation, there is a good chance that a self-perpetuating snow storm can be triggered off at a specific locality.

(7) The presence or lack of sublimation nuclei of spontaneous or foreign particle types. The spontaneous forms are present only if temperatures in the region containing suitable amounts of moisture are lower than -39°C. This could happen at cirrus levels and the crystals so formed could fall into lower supercooled clouds and thus serve as natural seeds [LANGMUIR, 1946]. Dry adiabatic lapse rates between the two cloud layers would favor such effects. The presence of foreign particles serving as sublimation nuclei undoubtedly is of much importance in the life of supercooled clouds. Much additional study is required to understand the nature of these particles as well as the reason for their unpredictable occurrence.

Fig. 3--Deck of supercooled clouds below the summit of Mt. Washington

There are many varieties of snow crystals which occur in natural snow storms. Attempts have been made in the past to establish classification systems to adequately describe the forms which are likely to occur in such storms. NAKAYA [1936], WEICKMANN [1945], and others have published such systems. In most instances these seem to contain too much detail or else they neglect to include some of the important forms. The writer has proposed [SCHAEFER, 1947] a classification system which divides all types of frozen precipitation, indluding sleet, into nine groups. This system has been used successfully for the past several years in studying the types of solid precipitation that occur simultaneously at selected stations in the northeastern part of the United States. The area in which this study was made contains more than 50,000 sq mi. At no time has precipitation occurred which could not be designated and coded by this system.

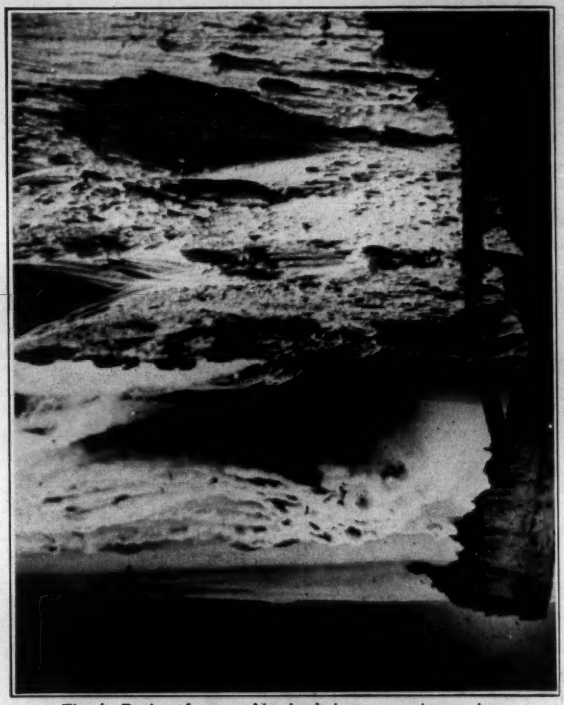

Fig. 4--Region of orographic clouds in same region as shown in Figure 2 but containing snow; snow fell in this region all day

While space does not permit a discussion of the results of the snow-storm survey, several interesting results should be mentioned since they have a pertinent relationship to the subject under discussion. In several instances wide-spread storms were found to have only stellar crystals over the entire region; in others, although a considerable variation in crystal form occurred, the change from one form to another proceeded in identical sequence over a large area. In growing crystals under definitely controlled moisture-temperature conditions in the laboratory, NAKAYA [1938] has shown that most of the variations of natural forms of crystals are a direct result of the environment in which they grow. Thus it is believed that much valuable information will result from a more careful study of the various forms of snow which fall during the progress of a storm. One of the significant occurrences in this respect is the rarity of perfect stellar crystals during a storm period. A fall of these beautiful crystals (most commonly used to illustrate typical snow forms) actually is a rare occurrence. Perfect stellar crystals fall at infrequent periods during any extensive snow storm and when they do, it is generally at the beginning or during lulls in the storm. The majority of snow particles that fall in an intense storm from clouds below 10,000 ft altitude are generally asymmetrical forms. Close study of these will show that many such particles consist of fragments of stellar crystals coated with irregular shaped angular growths. The vast majority of snow particles from low altitude clouds where the air temperatures are rarely colder than -20°C are of this general asymmetric form. This suggests the mechanism whereby nature produces tremendous quantities of crystals from relatively small numbers of crystals. It has been shown [SCHAEFER, 1947] that the falling velocity of tiny cirrus

type crystals is nearly as great as much larger ones since the area of the latter is greater and the density less. In fact, large, cottony snowflakes more than an inch in diameter, consisting of several score of large stellar crystals, often have falling velicites of less than one meter per second.

With these facts in mind, it is easy to visualize stratified regions in supercooled clouds where the upward air velocity would tend to accumulate snow crystals for considerable time periods. In such a region, the growth of crystals would be very rapid. Fast growth in crystals tends to form complex dendritic structures which are very fragile. With increased concentration abrasion between the tumbling particles would occur which would not only produce fragmentation but also triboelectric effects.

Recent experiments with high voltage in snow crystal clouds show that when snow crystals enter an electric field delicate and long fibrous growths appear on all surfaces within the influence of the field.

Thus it is easy to see a mechanism whereby Nature, starting with relatively few crystals, could, under proper conditions, produce tremendous quantities of tiny ice fragments, each of which would become the nucleus of a snow crystal. Thus an initial development of a limited amount of snow in a region of supercooled clouds could become self-perpetuating. This initial phase could occur either by the spontaneous development of ice crystals from air supersaturated with respect to ice having a temperature of -39°C or lower, or by the fortuitous presence of suitable foreign particles serving as effective sublimation nuclei.

In considering the possibility of obtaining precipitation from clouds in the form of snow or rain, it is desirable to obtain a proper perspective of the problem. First of all, it is pertinent to determine the amount of moisture contained in a fairly dense cloud mass. Assuming a thickness of 3500 m (about two mi) and a water content of one gram per cu m, it follows that if such a cloud were to be brought to Earth in its entirety and without lateral spreading or other modification, it would produce about 0.14 inches of water or about 1 1/2 inches of snow. This immediately points to the fact that if any appreciable amount of precipitation is to be obtained by the seeding of supercooled clouds, it is necessary to obtain more than the moisture contained in the particular cloud mass treated. The introduction of dry ice pellets into a region of supercooled clouds at the proper time and place serves as a trigger which may release a tremendous amount of potential energy. The course followed subsequent to this triggering action will depend in a large degree on the particular meteorological condition which obtains at the moment of seeding.

It is far too early at the present time to predict the results to be expected. Each experimental seeding flight made by the writer produced different results. A detailed description of these flights will be described elsewhere.

Modified clouds have been dissipated into long streamers of snow and have shown a subsequent growth in others. Some of the early seeding runs produced a hole in a solid overcast and others showed a deep subsidence. Experiments in Australia [KRAUS and SQUIRES, 1947] already mentioned have shown remarkable convective activity, one of the results indicating the production of an inch of rain from the seeded region. The experiment in Oregon reported a line of light showers below the seeded region, while, on Mt. Washington, members of the Observatory [HOWELL, 1947] produced snow showers by simply holding a piece of dry ice in the hand as supercooled clouds swept over the summit of the mountain. All reports to date serve to emphasize the point that positive effects will be obtained with dry ice seeding whenever and wherever supercooled clouds develop in the atmosphere. The results which will follow such activities will depend on many factors, some of which have been listed earlier in this paper.

The question is sometimes raised as to the quantity of nuclei produced by dry ice pellets. Semi-quantitative laboratory experiments show that tremendous quantities of nuclei are generated. In fact, a simple experiment shows that approximately 1×10^{16} nuclei per gram of dry ice are produced under favorable conditions. Thus a single pea-sized pellet could produce so many nuclei that if each grew to the size of a small natural snow crystal their aggregate weight would equal 300,000 tons. It is impossible to distribute the nuclei from a single pellet so that they all grow. It has been found that dry ice serves as a most effective substance to seed supercooled clouds in the natural atmosphere.

Recent developments in this laboratory by B. Vonnegut and the writer, propose the use of silver iodide for use in special cases especially where a continuous supply of nuclei is needed at ground stations.

The modification of supercooled clouds by artificial seeding operations seems to have intriguing possibilities. It permits us to affect naturally occurring but potentially unstable regions of the atmosphere. By using this technique to trigger off this unstability, enormous amounts of energy may be released by the use of a few pounds of dry ice.

Many problems remain to be solved before a proper perspective may be had of the potentialities of the method. Many investigations involving the acquisition of data by new methods and from new viewpoints will be required before it will be possible to evaluate the various aspects of the situation.

Fortunately, the conditions which lead to violent thunderstorms, devastating hail, serious aircraft icing, and disastrous sleet storms are nearly always associated with the occurrence of considerable densities and thicknesses of supercooled clouds in the sky. Wherever and whenever such clouds exist, it is possible to affect them profoundly and even to eliminate completely the supercooled condition, converting them to snow by the judicious use of relatively small quantities of dry ice.

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SOIL DETACHMENT BY WATER IN EROSION PROCESSES

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Abstract--Land erosion occurs as two independent events. The first is detachment, the tearing loose of soil particles; and the second is transporting them. Impact of rainfall consolidates some soils through compaction and cementation of particles. A soil that consolidates well and resists tearing apart, has low detachability. Soils of smooth grained sand which contain very little clay or other cementing materials have high detachability. During rainstorms there are two principal erosive agents which detach soil. Raindrops are one as they splash the soil surface. Flowing surface water is the other, as it runs off the land. Splash of raindrops detaches most of the soil carried off smooth surfaces of the land outside of rills and gullies. It has been estimated that these splahses may throw more than 100 tons of soil per acre several inches into the air during a beating rainstorm on a bare field of highly erodible soil. Surface flow detaches most of the soil that is removed from within gullies.

Detached soil particles are ready for transport and represent an erosion hazard. The probability of detached soil particles being carried away varies with the transportation hazard. The steeper the slope, the greater this transportation hazard will be. Magnitude of detachment hazard that can be safely tolerated depends on the hazards of transportation. Soil detachment hazards are measurable, and they can be effectively reduced by erosion control measures and practices. To design effective controls we must first determine (1) the detachability of the soil; (2) the detaching capacity of each erosive agent; and (3) the effects of impediments to the detachment process such as vegetation.

Soil erosion is a process of detachment and transportation of soil materials by erosive agents [ELLISON, 1946]. Detachment is the tearing loose of soil aggregates or particles of transportable sizes from their moorings in the soil mass. This may be expressed in terms of pounds or tons per acre. Transportation is the moving through distance of detached parts of soil and it is expressed in terms of weight through distance such as ton-miles. Transportation may also be referred to the contributing area and expressed as ton-miles per acre. Thus we see that these separate and independent variables of soil detachment and transportation cannot be combined in practical field work because they cannot be expressed in like units.

It is not only impossible to express soil erosion as a single numerical value but it is also impossible to make direct quantitative measurements of soil erosion on open fields. This is because some of the soil detached is transported only a matter of inches, some is transported several feet while some may be transported hundreds of feet or carried entirely off a field

Since we cannot measure the erosion for each storm on open fields, we usually measure soil loss and attempt to use these values as a basis for soil erosion studies. But there are other measurements we can make, such as soil detachment and transportation hazards. The detachment hazards will vary with changes in (1) the soil; (2) the erosive agent; or (3) impediments as detachment.

Each soil may vary in its detachable characteristics, as well as in its transportable characteristics. In Table 1 we have listed the most detachable soil at the top of the left-hand column and the most transportable soil at the top of the right-hand column. In general, clays are of low detachability and high transportability, while sands are usually of high detachability and low transportability. Because of this we would say that both clays and sands are generally of low erodibility; clays, because they are difficult to detach, and sands because they are difficult to transport.

Table 1--Detachability and transportability of soils

Detachment	Transportation
Sand	Clay
Loam	Loam
Clay	Sand

In addition to the effects of the soil's detachability and its transportability on erosion, we also find differences in the detaching and transporting capacities of the erosive agents which also cause variations in the soil erosion

processes. Differences in these capacities can be illustrated by citing some exploratory experiments made by the writer. In the first test surface flow consisting only of clear water was passed over a clay bed. This caused very little erosion because it would not detach the clay. The water flowed off the lower end of the plot almost clear.

In a second test some soil containing abrasive materials was injected into this water at the point where it flowed onto the clay bed. This abrasive material increased the detaching capacity of the flow and greatly accelerated erosion. When increased amounts of this soil material were injected into the water entering the plot, the detaching capacity was increased and the transporting capacity (amount of detached soil that could be transported) was decreased. The amounts of soil added could be increased until all of the transporting capacity would be absorbed in transporting the injected soil. This would then stop further erosion because detached soil, unless replacing injected soil, could not be carried off.

To summarize, when only clear water was applied there was maximum transporting capacity and minimum detaching capacity, and very little erosion. When the water applied was fully charged with soil, there was maximum detaching capacity, minimum transporting capacity, and again there was very little erosion. The maximum erosion would occur when the detaching and transporting capacities of the flow were of similar magnitude, that is, when the flow contained just enough abrasive materials to detach as much soil as it could carry. The relationships between detaching and transporting capacities which will prove to be most erosive will change with each change in the soil's erodible characteristics. Therefore, a condition of flow which is found to be most erosive on one soil, may not be most erosive on another soil.

If we measure the detaching capacity of the erosive agent and the detachability of the soil, we can then compute the soil detachment hazard for a bare soil. The same can be said for the transportation hazard. These two hazards must be coupled to cause erosion. Either may appear singly on a field without causing soil loss. Generally, high transportation hazards are associated with steep slopes, and high detachment hazards are associated with bare soils,

After we have determined the hazards of soil detachment and its transportation, we must be able to evaluate corrective measures which may be used in reducing or even eliminating these hazards from a field. This will require that in evaluating the effectiveness of erosion control measures, their effects on soil detachment be evaluated separately from their effects on soil transportation. After this has been done, we can match a detachment hazard with a control measure and eliminate the hazard. The same procedure will apply to the transportation hazards.

The foregoing is by way of explaining some of the aspects of the soil detachment problem. Let us now consider some of the specific methods used to evaluate the factors entering into and controlling the magnitude of the detachment hazard. These separate factors can be summed up in a detachment equation as follows:

$$D_1 = f(D_2, D_3, R) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where D_1 = the amount of soil detached, D_2 = the detachability of the soil, D_3 = the detaching capacity of the erosive agent, and R = a relative resistance factor for expressing control measures effects on the detachment process; this factor is unity for a bare soil and it increases with vegetal or mulch cover.

A falling raindrop will detach soil through a splash process at the point of its impact. The flowing surface water detaches soil by a scouring process as the water flows downslope. Detachment by raindrops will include the entire surface of a bare field, and when this soil is transported away it will produce a sheet-erosion effect. Detachment by surface flow is usually limited to rills and gullies. The idea that surface flow acts somewhat like a grader blade, scouring from a broad surface of the field is thought to be faulty; flowing surface water usually scours in channels only and produces a gully-erosion effect. Because of these great differences in the erosive effects of raindrops and surface flow, the two cannot be combined and treated as a single erosive agent, but the detachment equation must be applied to each of these agents separately.

Let us now consider applying (1) to the falling raindrops. To measure these separate D-factors, a standard material is introduced so that all might be expressed in like units and in terms of this standard. This material serves as a standard soil, and it is made up of a fine, round-grained sand which passes through a 60-mesh sieve and is retained on a 70. The detaching capacity (D_3) of falling raindrops is a function of the drop-size, drop-velocity, and rainfall intensity, or

$$D_3 = f(V, d, I) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where, V = velocity of raindrops, d = diameter of raindrops, and I = intensity of rainfall.

For an eroded Muskingum silt loam [ELLISON, 1944] the combined detachment and transportation processes were found to be a product of $V^{4.33} d^{1.07} I^{0.65}$. The relationships have not yet been established for our standard soil and it is hoped that such an investigation can be made soon.

Pending the time we may be able to measure and apply results of our measurements on drop sizes and velocities for natural storms, another technique is used in which we only measure the effects of the splashing raindrops. Methods for making such measurements are fully explained in another paper [ELLISON, 1947]. These consist of placing a known weight of our standard soil in a small dish and exposing it to the splash of falling raindrops. After rainfall it is again weighed to determine the amount splashed out of the dish. The detaching capacity of the raindrops is then assumed to be equal to the amount of the soil splashed out of the small dish.

Having evaluated the D_3 factor, we now only need a value of D_2 (the soil's detachability) to enable us to compute D_1 (the detachment hazard caused by falling raindrops) on a bare soil. A method for measuring D_2 was previously reported [ELLISON, 1947]. It was based on exposing a soil surface simultaneously beside a surface of standard soil (fine sand) and measuring the amount of splash on each. If the splash on the soil being tested is 60 gm and that on the standard soil is 100 gm, then the soil's detachability is 60/100 = 0.60.

Since we have used the same standards for each measurement, we can now write (1) for a bare soil surface, $D_1 = D_2 \times D_3$. If in our experiment we measured a D_3 of 100, and D_2 of 0.60, then $D_1 = 0.60 \times 100 = 60$. From a comparison of areas and weights (we used a dish 3-1/2 inches diameter to measure D_3, and our weight of splashed material was expressed in grams) we find that by multiplying the detachment of 60 by 3/4 we convert this hazard to tons of soil per acre. For this rainstorm the splash would be $60 \times 3/4 = 45$ tons per acre.

Soil which is detached by the splash process represents a hazard in many ways. We are interested in it here as an erosion hazard. It represents an erosion hazard because in a detached state it is liable to be lost from the field. This liability or probability will depend on the steepness of the land and on other conditions which affect the transportation hazard. On very steep land we like to keep the soil covered continuously because we recognize a transportation hazard so great that most all of the detached soil will probably be carried away.

After we have evaluated a detachment hazard for a bare field, the next step is to select crops and cover practices which will make D_1 approach zero, or at least reduce it to some low value which will achieve our conservation objectives. Before we can do this we must evaluate the effects of different types of soil covers. Here again the standard soil is used with two small test areas. In one of these test areas the vegetal cover is all removed and the surface is covered with the standard soil. In the second test area which is of equal size, the standard soil is spread beneath the vegetal cover. With this arrangement the only difference in the splash on the two areas will be caused by the vegetation. If 100 gm of splash is measured on the area free of vegetal cover and only five gm of splash is measured within the area containing the vegetal cover, the resistance value of the cover is 100/5 = 20. Now (1) can be written for the conditions of $D_2 = 0.60$, $D_3 = 100$, and $R = 20$, $D_1 = 0.60 \times 100/20 = 3.0 \times 3/4 = 2.25$ tons per acre. If a smaller detachment hazard than 2.25 tons per acre is wanted (raindrop detachment only) then a vegetation or mulch or both, with an R value greater than 20 will be used. This procedure enables us to design conservation practices which maintain the detachment hazard at any practical, low level desired.

The same detachment equation may be used in working with the surface flow. However, when treating of the surface flow it would be well to designate the different D factors as D′ so as to distinguish treatment of this agent from that of the falling raindrops. Until more work is done on evaluating the D'_2 factor for conditions of surface flow, it is suggested that the D_2 values obtained with the raindrop tests be substituted in this equation. When this is done, only the D'_3 factor needs to be evaluated in order to apply the detachment equation to surface flow on areas free of variable R values.

The value of D'_3 will be function of (1) the energy of the flow, (2) the abrasive properties of the soil in transport, and (3) the amount of abrasive materials in the flow, or

$$D'_3 = f(V^2/2g, \beta\, m) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where $V^2/2g$ = the energy gradient of the flowing materials, and β = the abrasive properties of the soil materials in transport, and m = the concentration of abrasive materials in the flow.

The writer started a series of experiments at Coshocton, Ohio a number of years ago for the purpose of evaluating the D'_3 factor. Unfortunately these experiments were run on soil and each time soil materials were detached, the value of β underwent change. Recently the writer had an extensive conference with J. C. Hide, O. T. Ellison, O. W. Monson, and others at Montana State College, Bozeman, Montana, and some new experiments were discussed. In these a standard soil will be developed. The properties of this standard soil will be such that detached particles will not be appreciably abrasive, and they will be so highly transportable that when detached, they will rise into the body of turbulently flowing water and float away. This will prevent the detached materials from changing the abrasive characteristics of the flow. The energy of flow will be held constant, for a series of experiments, and β will be a temporary constant (constant for soil type). Soils A, B, and C will each represent a different value of β, and so, while holding $V^2/2g$ and m values constant, soils A, B, and C will be injected one at a time into the current. This work is in an exploratory stage, exploring for methods, and one cannot predict results at this time.

When the detachment is caused by flowing surface water, the resulting erosion will produce rills and gullies. According to the detachment formula, we may check this detachment through manipulating either D_2 or D_3. From (3) we learn that D_3 may be reduced either by reducing $V^2/2g$, or by reducing m values, or by a less abrasive soil which will lower the β factor. On soils of very high detachability, a flow of clear water may cause high rates of detachment. On these soils the most effective check will be velocity reduction. To desilt the flow may actually accelerate downslope erosion on these soils. But on soils of low detachability, the most effective way of checking detachment may be through reducing the m and β factors (through desilting the flow). On these latter soils, strip cropping which removes abrasive materials from the flow at each filter strip may be a very effective erosion control practice on open fields. But on soils of high detachability such a practice may be of little value.

The values of R' in the equation of detachment by surface flow will reflect impediment values. Stems of vegetation, contour ridges, terraces, and various other obstructions will impede the surface flow and each will have a specific R' value. However, it is not possible to determine these R' values until we have learned just what they are to resist and impede by first evaluating D'_3. Because of this, our progress in completing methods for measuring each of the factors in the detachment formula applying to surface flow is delayed temporarily, awaiting some progress on the work of evaluating D'_3.

Before we can do our most effective work in soil erosion control, it will be necessary that we know the values of the erosive agents that do the eroding, the values of the soils that are eroded, and the values of the corrective measures and practices that are used to check the erosion. Since erosion cannot be expressed as a single quantitative value, we have to use at least two equations, one for soil detachment hazards and one for soil transportation hazards. The methods presented in this paper pertain to the detachment hazard only. These would be evaluated through measuring the detachability of the soil, the detaching capacity of the erosive agent, and the resistance to detachment offered by the erosion control measures and practices.

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DEVELOPMENT OF LIMESTONE RESERVOIRS IN COMAL COUNTY, TEXAS

William O. George

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Abstract--The Edwards limestone, and to a lesser extent the Comanche Peak limestone and the lower part of the Glen Rose limestone below, all of Lower Cretaceous age, form one of the most extensive ground-water reservoirs in Texas. As a result of normal faulting, these formations are connected by underground channels to form a hydrologic unit which is partly artesian and partly unconfined. Observations in Comal County show that the development of the reservoir by solution is closely related to the geologic history, in which complex faulting and the disconformity between the Edwards and Georgetown limestones are important factors. Various phases of development are shown in different fault blocks, depending upon length of exposure at the surface. The Edwards limestone, which contains the main channels of underground drainage, is almost uniformly permeable from top to bottom, whereas the older, but more recently exposed lower part of the Glen Rose limestone is generally relatively impermeable except where exposed by mature streams.

Introduction

This paper presents some of the observations made in Comal County, Texas, as a part of a continuing study of the ground-water resources of the Balcones fault zone by the United States Geological Survey in cooperation with the Texas State Board of Water Engineers. The study was started by SAYRE [1936] in 1928, and has been carried on [LIVINGSTON, SAYRE, and WHITE, 1936; LIVINGSTON, 1942 and 1947] up to the present time.

The limestone reservoirs are distributed along the Balcones fault zone (see Fig. 1) from Kinney County through Uvalde and Medina Counties, Bexar, Comal, Hays, and Travis Counties in south-central Texas. In the central part of the zone there are large flowing wells [LIVINGSTON, 1942] and springs, notably a well in San Antonio that yields 16,800 gal/min by natural flow and Comal Springs at New Braunfels in Comal County, which has an average discharge of 323 cfs or 145,000 gal/min.

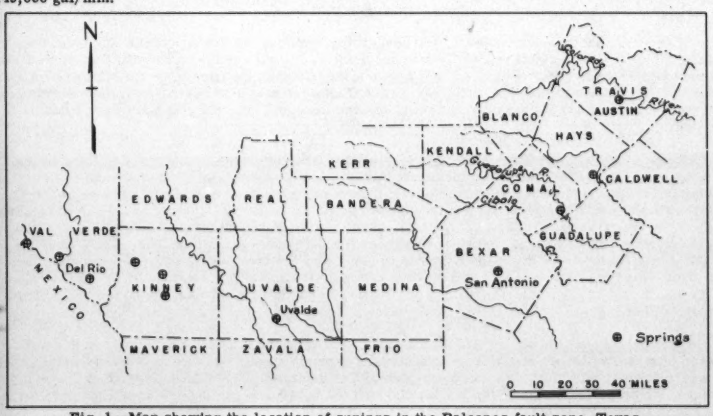

Fig. 1--Map showing the location of springs in the Balcones fault zone, Texas

Geologic and physiographic setting

The outcropping Cretaceous rocks in Comal County range in age from the Cow Creek member of the Travis Peak formation at the bottom to the Taylor marl at the top.

There is evidence of almost continuous deposition beginning with the Travis Peak formation and continuing to the end of Fredericksburg time. The absence of the Kiamichi formation and several members of the Washita group indicate a hiatus covering a period of considerable geologic time after Fredericksburg time. According to STEPHENSON [1929] and to ADKINS [1932], evidences of disconformity are also found at the upper limits of the Buda limestone, the Eagle Ford shale, and the Austin chalk. The wide range of stratigraphic exposure is made possible by seven normal strike faults having a total displacement of about 1500 feet and by a total topographic relief of about 900 feet. In general, the dip of the rocks is southeastward and is gentle except in the vicinity of major faults where dips up to 15° are common. The Guadalupe River flows in slightly entrenched meanders across the central part of the county in a course more or less transverse to the strike of the faults, as shown in Figure 2. Cibolo Creek, which forms the southwest boundary of the county, also crosses several faults and is in a similar stage of maturity.

Springs

Comal Springs--Because of its magnitude, Comal Springs is the focal point of ground-water studies in Comal County. The average flow of Comal Springs from 1928 to 1945 was 323 cfs or about 200 mil gal/day. This is greater than the runoff from 1432 sq mi of drainage area in the Guadalupe River Basin above the spring during the same period. The uniformity of discharge is indicated by the fact that the minimum flow is 75 per cent of the average discharge. The water issues from the Edwards limestone at the foot of a 100-foot fault escarpment. It is never turbid and the temperature does not vary more than 1/2 a degree from 74° F, which is six degrees warmer than the average annual temperature at New Braunfels. The point of discharge is about a mile from the Guadalupe River, which is about 40 feet lower than the springs.

Hueco Springs--Hueco Springs is about three miles north of Comal Springs. It is at the intersection of a major fault and the Guadalupe River and is about ten feet above the level of the river. Discharge measurements of record range from zero to 93 cfs. The temperature ranges from 68° F to 71° F. At times the water becomes slightly turbid.

The differences in the characteristics of the two springs show that the source or intake area for Comal Springs is immense and distant, whereas the source of Hueco Springs is probably nearby and relatively small.

Reservoir rocks

The main underground reservoir and conduit that supplies the springs is the Edwards limestone, which is 400 to 500 ft thick. This is supplemented locally by the underlying Comanche Peak limestone, which is about 40 ft thick, and by the lower 400 ft of the Glen Rose limestone below. Massive limestones in the uppermost part of the Glen Rose may also contribute to the reservoir where the marl of the Walnut clay, between the Glen Rose and the overlying Comanche Peak, is absent.

Edwards limestone--The greater part of the Edwards limestone is composed of thick beds of dense, gray crystalline limestone containing rudistid and caprinid fossils. Some beds, of flagstone thickness, have porcellaneous texture. Lenses of red clay up to 40 ft in thickness, probably secondary deposits formed by natural puddling during an earlier episode of cave development, have been reported by drillers. Irregularly shaped nodules and thin lenses of chert occur at several horizons. The Edwards lies conformably on the Comanche Peak limestone. The Comanche Peak is not distinguished from the Edwards limestone by drillers, and in this paper for purposes of discussion the two formations will be referred to as the Edwards limestone. They are also shown as a unit in Figure 2. In its outcrop area the Edwards is cavernous and honeycombed from top to bottom.

Comanche Peak limestone--The Comanche Peak limestone is about 40 ft thick and is composed of massive limestones with an abundance of caprinid fossils. In most places in Comal County the formation seems to be about as permeable as the Edwards. Below these formations, in some places, the clays and marls of the Walnut clay and the upper part of the Glen Rose limestone form an effective barrier to the downward percolation of water.

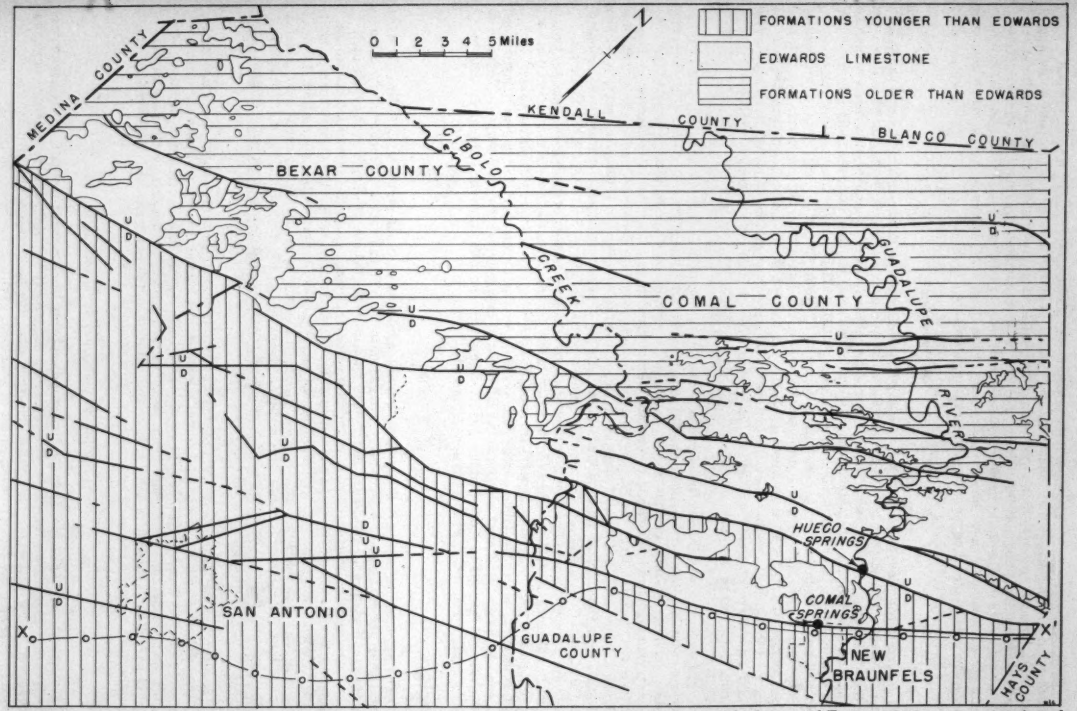

Fig. 2--Geologic map of Comal County and a part of Bexar County, Texas; Bexar County after geologic map of Texas, USGS, 1937; extension of line X-X' (limit of potable water) into Bexar County as determined by Livingston, Sayre, and White

Glen Rose limestone--The Glen Rose limestone is about 1000 ft thick. The upper 600 ft are composed of alternating shales and limestones and contain very little water. A few beds containing fine sand, however, provide small yields for farm wells. The lower 400 ft of the Glen Rose are predominantly limestone. At the outcrop the rock is honeycombed, especially in biohermal deposits where the shells of the fossils are dissolved, leaving only molds of the shells. Where the main streams have cut down into the lower part of the Glen Rose, the rock is cavernous, but where the lower part is under cover it is relatively impermeable.

Effect of disconformity

There is some evidence that the present permeability of the Edwards limestone is caused, in part, by solution by meteoric waters following uplift and before the overlying beds were deposited by the encroaching Georgetown sea. In Bexar County, honeycombed or cavernous zones are found in the Edwards far from the outcrop beneath a thick cover of younger and relatively impermeable rock. In one well, 11 1/2 mi south of San Antonio [LIVINGSTON, 1947], honeycombed limestone was reported near the top of the Edwards at a depth of 2773 ft; in another well about 14 mi south of San Antonio and about 25 mi from the nearest outcrop, a core of porous limestone was obtained in the formation at 2878 ft; in still another well in the City of San Antonio, 12 mi from the nearest outcrop of Edwards limestone, a seven-foot cavity was reported at a depth of 930 ft. Such a cavity could hardly be of primary origin and is probably too far from the source of carbon dioxide-bearing waters to be of recent origin.

The water in the Edwards limestone becomes more highly mineralized down dip, and it is assumed that the downward limit of potable water marks the limit of free circulation of meteoric water. In Bexar County, the line X - X' (see Fig. 2) between good and bad water extends far into the artesian area and to depths where the top of the Edwards is 1500 ft below the surface. The northeastward extension of the line cuts diagonally across the strike of the formations and thence follows a major fault in Comal County which separates the water-table area on the upthrow side of the fault from the artesian area on the downthrow side. There is no potable water in the artesian area in Comal County and for that reason very few wells have been drilled and little is known about the permeability of the Edwards limestone, but the poor quality of the water suggests that there is not much circulation of meteoric water in that area. The reservoir rock, covered by more than 500 ft of relatively impervious rock, is probably in its primary condition except for such solution as may have taken place prior to the deposition of the overlying younger formations. In general, the circulation of water and the direction of movement of the main body of ground water toward Comal Springs is more definitely related to faults and other structural features than to the over-all permeability of the Edwards limestone.

Faults

The seven major faults in Comal County are roughly parallel and strike from 50° to 65° northeast. They are normal faults forming structural stair-step blocks that are progressively downthrown to the southeast. In upward succession toward the northwest, the trace of the first fault passes through New Braunfels and it is called the Comal Springs fault; the second intersects the Guadalupe River at Hueco Springs and is called the Hueco Springs fault. The Comal Springs fault has a displacement of about 500 ft and forms an escarpment of Edwards limestone about 100 ft high. No other fault escarpments are found in Comal County but rapids are found at most stream intersections. The Hueco Springs fault displaces from 300 to 400 ft of strata but the trace of the fault is not well defined, being more of a fault zone characterized by the occurrence of fault breccia composed of limestone boulders and clay, cemented by flowstone or caliche.

Southeast of the Comal Springs fault, the Edwards limestone is buried under about 500 ft of younger and relatively impervious formations; between the Comal Springs fault and the Hueco Springs fault, the Edwards is only partially covered by thin remnants of younger formations. Continuing northwestward, in each fault block the Edwards becomes progressively thinner. In the central part of the county it is found only on the hill tops and in the northwest part of the county it has been completely removed by erosion.

Interpretation of solutional development

Solutional cavities in the Edwards limestone probably were already partially developed before the overlying Georgetown limestone was deposited, but the pattern of this development is not known. Subsequent faulting fractured the brittle limestone along the fault planes and provided access of meteoric water for the further development of solutional cavities, beginning in the higher fault blocks to the northwest and progressing to the lower blocks to the southeast as the protective

cover of younger shales and limestones was removed by erosion. As solution channels along the fault planes developed into larger caverns, a network or spongework of smaller openings developed laterally and at lower levels until the blocks between the faults became more generally permeable. In some places between the Comal Springs and Hueco Springs faults, remnants of the Washita group and, in a few places, of the Eagle Ford shale and Austin chalk, are found in depressions at levels below the general present level of the Edwards limestone surface. It is not quite clear whether the sinks are pre-Washita in age, indicating simply disconformity, or whether the sinking took place gradually as undermining by solution progressed. The latter explanation was proposed by UDDEN [1918, pp. 14-15] in a report describing similar conditions in the Terlingua Mining District of West Texas.

In the later stages of development, the larger caverns were partially filled with the red clay residue of dissolved limestone, followed by filling with limestone fragments, gouge, and clay, cemented with flowstone. The clastic material may have been carried by vadose streams but little evidence of stratification was found in the present outcrops of the filled material. Thus, the channels that were the main conduits in the earlier stage of development finally became effective barriers that control the direction of the movement of water

Effect of physiographic development

On the relatively flat upland surface formed by the outcrop of the Edwards limestone, sinks up to 15 acres in extent are present but are sparsely distributed. Most of these larger sinks hold water for several weeks after heavy rains. The smaller inconspicuous caverns and honeycombed rocks, however, probably provide access for infiltration of a large percentage of the rainfall. There is no typical karst topography.

The superposed patterns of the Guadalupe River and of Cibolo Creek appear to be only slightly affected by the faults that cross them. Rapids occur at most fault intersections (see Figs. 3 and 4). Some of the tributaries, however, follow fault lines.

In areas where the bedrock of the main streams is the lower part of the Glen Rose limestone, development by solution appears to be more or less inversely proportional to the distance from the two streams. This is probably caused not only to the protection of overlying formations in the interstream area but also to the length of time the rocks have been exposed, as indicated by the age of the streams. In the interstream area, only small amounts of water are available to wells; along the main streams the underlying rocks are more cavernous and larger yields are obtained. In the vicinity of Cibolo Creek, in Kendall County, a cavity one ft in depth at 270 ft has been reported. The water rose to a level 200 ft below the land surface. Caverns in the flood plain of the Cibolo are numerous, particularly where the bedrock is the lower part of the Glen Rose limestone (see Fig. 5).

Sources of water

The average annual precipitation in Comal County is about 31 inches. In order to account for the average discharge of 200 mil gal/day at Comal Springs, and the significant but less spectacular flow at Hueco Springs, it is obvious that a large intake area is required or that there are contributing losses from streams that drain large areas. The Guadalupe River above Comal Springs has been investigated as a possible source of water that might be conducted through underground channels to the Comal Springs reservoir. In the northwest part of the county the lower part of the Glen Rose limestone is honeycombed and cavernous, and there are some sinks. In the vicinity of the river there are some wells that suggest considerable solutional development because of their apparent high potential yield. Water levels in these wells, however, are higher than the level of the stream, indicating that the river is effluent. Two series of seepage measurements made by the United States Geological Survey in 1928 and 1929, during periods of low flow, show that most of the small amounts of water observed to be lost from the upper part of the stream are returned to the river as small springs above Hueco Springs. Therefore, losses from the Guadalupe River are believed to be negligible. It is believed that solutional development in the limestones along the Guadalupe River channel has been retarded because of the lack of an outlet for percolating waters except the channel itself. The distance to the Comal Springs reservoir from the part of the Guadalupe River where the lower part of the Glen Rose limestone is exposed and where the greatest solutional development has taken place, and the possible damming effect of the Hueco Springs fault, have probably prevented the formation of underground channels from the river to the reservoir feeding Comal Spring.

Fig. 3--Guadalupe River at Hueco Springs fault

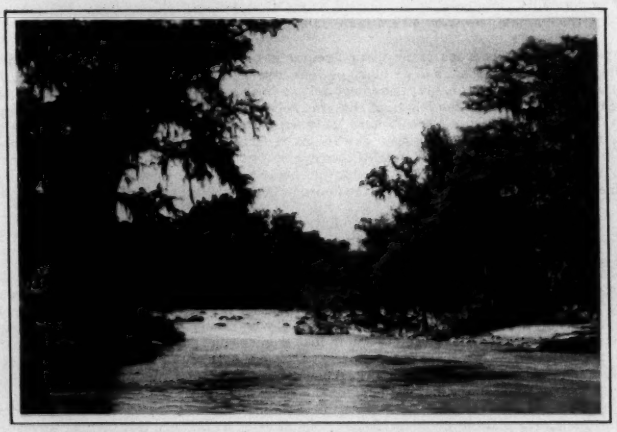

Fig. 4--Guadalupe River at Comal Springs fault about three miles northeast of New Braunfels; rapids mark position of fault which brings Edwards limestone in contact with Taylor marl

A similar investigation was made along Cibolo Creek, which crosses the same sequence of formations and also crosses several fault blocks, and the runoff data for the Guadalupe River and Cibolo Creek were found to be remarkably different. Gaging stations have been established only recently on Cibolo Creek, but during the brief period of one year, beginning March 1, 1946, the runoff from the Cibolo basin was 41.7 ac ft/sq mi, compared with 721.3 ac ft/sq mi from the Guadalupe River basin in the same general area and receiving about the same amount of rainfall. In August 1946, a six-inch rain fell within 48 hours on the upper part of the Cibolo basin in Kendall County (see Fig. 1), and about five inches fell in the western part of Comal County. Immediately

Fig. 5--Cavern in lower part of Glen Rose limestone in flood plain of Cibolo Creek

after the rain, an estimated discharge of 300 to 500 cfs was observed in Cibolo Creek at the western corner of the county but this discharge was lost within five miles below this point and within a few hours there was no flow in Ciblol Creek anywhere in the county. It is believed that these heavy losses are possible because of underground channels leading to the Comal Springs reservoir. The proximity of the Cibolo basin to the reservoir makes this plausible, but more data on water levels in wells in the intervening area are needed to support this conclusion. In spite of the impressive losses in the Cibolo Creek basin, the volume is probably considerably less than the discharge of Comal Springs.

The area of direct infiltration of rainfall on the outcrops of Edwards limestone in Comal County is comparatively small. All the area east of the Guadalupe River can be eliminated because the hydraulic gradient as shown by water-level measurements in wells in that area is northeastward, indicating movement away from the springs rather than toward them. West of the river and north of the Hueco Springs fault, the Edwards is exposed over a comparatively large area, but the infiltrated water drains toward the fault where it is intercepted and diverted to Hueco Springs. In those fault blocks where the Edwards is thin it drains rapidly, and it is necessary to drill water wells to rocks below the Edwards even to obtain enough water for ranch use. Near the Hueco Springs fault, ample supplies of water are available from the Edwards. Water levels in wells on the downthrow side of the fault near Hueco Springs are lower than the level of the point of discharge of the springs.

Similarly, the Comal Springs fault is a confining wall because the Edwards limestone is entirely displaced and is more or less sealed by contact with the Taylor marl on the downthrow side of the fault. In the eastern part of Bexar County, LIVINGSTON and OTHERS [1936] have shown that there is an abrupt change in the direction of the movement of water and it is believed that

a considerable volume of water moves from the artesian area of Bexar County to the water-table area of Comal County, thence between the Hueco Springs fault and the Comal Springs fault to Comal Springs.

Conclusions

The greater part of the necessarily large ground-water reservoir that supplies Comal Springs lies west of Comal County. The reservoir has been developed as a result of solution during the period before the rocks overlying the reservoir were laid down and by subsequent solution along faults which now control the direction of movement of the water. This natural underground reservoir, which releases its water at a relatively uniform rate for beneficial use, is probably no small factor in the control of floods in the areas west of Comal County.

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RUNOFF FROM RAIN AND SNOW

(A review of concepts and principles with relation to forecasting seasonal water supplies, and particularly to the effects of ground water)

Arthur M. Piper

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Abstract--The basic principles of the idealized hydrologic cycle are reviewed with emphasis on storage and movement of water in the soil. A distinction is made between ground-water runoff and overland runoff in terms of storage and lag, expressed as accumulated deviations from uniform flow over a period of several years. These functions are presented for the period 1920 through 1945 for three rivers in central Oregon: John Day, Deschutes, and Metolius, which exemplify minimum, moderate, and maximum effects, respectively, of storage and lag. The Metolius River is shown to have extremely small fluctuations in discharge from year to year, ascribed to a great portion of its flow being derived from ground-water runoff; and its response to fluctuations in annual precipitation lags behind that of the John Day River by about five years. Specific techniques and measures for improving seasonal water supply forecasts are suggested.

The purpose of this paper is to reiterate principles that apply to certain elements in the hydrologic cycle of a land area (see Fig. 1), with emphasis on the disposition of water that infiltrates the land surface and with relation to forecasting the flow of streams. Examples and concepts are drawn from and to suit the Pacific Northwest. For a comprehensive treatment of these principles the reader is referred to the text and bibliographies of Hydrology, Volume IX in the series on the Physics of the Earth published under the sponsorship of the National Research Council by McGraw-Hill in 1942.

Of rain that falls on an unfrozen terrane, a small part is intercepted by and evaporated from the vegetation and from the surface of the soil, another part penetrates below the land surface by infiltration, and the remainder is discharged immediately to the streams by overland runoff. Thus, other relevant conditions being equal, the runoff characteristics of a given terrane express its infiltration capacity.

Infiltration

The potential amount and rate of infiltration are determined primarily by the size and continuity of openings in the materials which form and lie immediately below the land surface (or which compose the vegetative litter on the land surface). Neither size nor continuity of these functional openings is constant because as the material is wetted its "colloid" component swells and aggregates of small particles commonly disintegrate, because the smaller openings may fill with water quickly and then become nonfunctional, also because small particles of soil may be entrained by infiltrating water and then may lodge across a small opening. Thus, infiltration capacity is not constant. Among dry soils and other surficial materials of relatively fine texture, its ordinary range is from less than an inch to about four inches an hour; within minutes or a few hours of continual rainfall on those same materials, its diminished rate may be as little as one-fourth of the initial value. On the other hand, among certain coarse materials such as talus, gravel, and volcanic ejecta it doubtless exceeds four inches an hour and may diminish much less rapidly.

In field terms, the infiltration capacity of a stream basin is influenced by varied factors. Thus, other conditions being equal, (1) in fine-grained surficial materials the principal openings by which water can infiltrate may be the casts of decayed roots, worm trails, and the burrows of rodents; (2) virgin terranes appear to have greater infiltration capacity than intensively cultivated area, at least in part because tillage destroys many openings such as just enumerated, and tends toward a progressively more compacted surficial layer; (3) tillage marks on cultivated land and depressions on rough terranes both trap water during storms and so extend the period of infiltration into the ensuing rainless periods; and (4) infiltration decreases with increasing slope of the land surface.

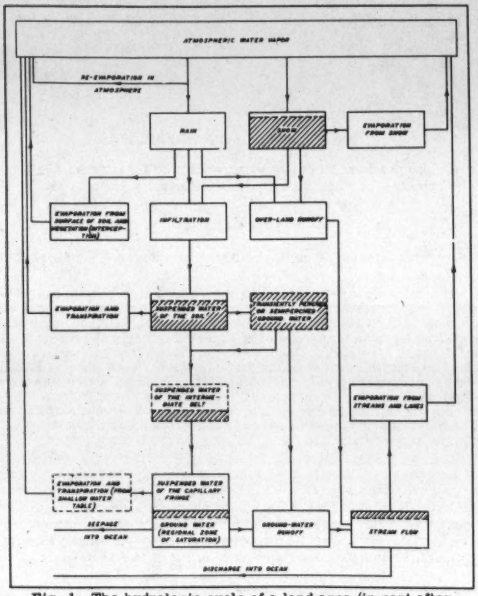

Fig. 1--The hydrologic cycle of a land area (in part after "Physics of the Earth, Volume IX, Hydrology")

The diverse land forms and surficial materials of the Pacific Northwest span a very wide range in potential infiltration capacities. At one extreme, over extensive areas and for dry conditions the potential capacity probably is equivalent to no more than an intermediate intensity of rainfall, and within a period much shorter than the common duration of storms the capacity may diminish to the vanishing point; in other words, a large proportion of the rainfall is rejected to overland runoff. Such conditions apply to old terraces of the Willamette Valley in Oregon, and to plains of glacial till in the Puget Sound area of Washington. At the other extreme, for certain areas the potential capacity doubtless exceeds the intensity of rainfall except during the most severe storms; that is, only a small proportion of the rainfall is rejected to immediate runoff. The striking example of this extreme is afforded by areas of young volcanic ejecta on the east flank of the Cascade Range in Oregon, where many square miles lack integrated stream courses and are drained almost wholly by infiltration. Within this wide range, the amount of overland runoff from a given amount of rainfall varies greatly, both from place to place within the region and according to rainfall intensities and storm durations over a particular part of the region.

Suspended water in the zone of aeration

Specific retention--Infiltrated water percolates downward through the zone of aeration, which extends from the land surface to some underlying zone or zones in which the interstices of the rocks are saturated with water. As the terminology implies, in this zone of aeration the interstices are in part filled with air and such water as exists either is in transit downward by gravity, or is suspended by adsorption to the surfaces of rock particles. Here, hydrologic phenomena are determined largely by the capacity of the material to suspend water against gravity. This capacity at least approximates a constant for material of a given texture; it is expressed technically as specific retention, which is the percentage ratio of (1) the volume of water which the material, having been saturated, will retain against the pull of gravity, to (2) the volume of the material [MEINZER, 1923, p. 28]. Students of agriculture commonly express specific retention as "water-retaining capacity" or "field capacity," in percentage of the dry weight of the material rather than in percentage by volume.

Specific retention ranges widely for the common surficial materials. In assorted coarse sand and in materials of even larger grain size, its magnitude is equivalent to water in a depth of less than an inch for each foot thickness of the material; in clay, the corresponding amount of retained water reaches, or may even exceed 50 per cent or six inches per foot of thickness. With this range of magnitudes, over a very large part of the Pacific Northwest the surficial materials have textures such, and the zone of aeration is sufficiently thick, that the aggregate capacity for suspended water greatly exceeds the yearly rainfall.

The concept of specific retention leads to the concept that infiltrating water wets a material fully or not at all. Specifically, as water infiltrates into the zone of aeration, it must satisfy any deficiency in the amount of suspended water before any can pass to greater depth. In other words, a limited amount of infiltrate may be dissipated into suspended water, with essentially none reaching a zone of saturation. As will be brought out, this concept is critical with respect to the relation between rainfall and runoff.

Subdivisions of the zone of aeration--With respect to hydrologic characteristics, the zone of aeration may be divided into three distinctive belts, as follows: (1) The belt of soil water is that from which moisture is dissipated by evaporation or is extracted by the roots of vegetation. Commonly it reaches no more than about ten ft below the land surface but, under certain conditions and with certain species of vegetation, may reach several tens of ft. (2) The intermediate belt is that which intervenes below the reach of evaporation or of extraction by vegetation, and from which water is discharged only by percolation downward. If the regional water table is at shallow depth, no intermediate belt may exist. (3) The belt of fringe water, or the capillary fringe, which lies immediately above a zone of saturation and whose water content exceeds the specific retention of the material owing to capillary rise from that zone of saturation.

Soil water--In the process of growth, the roots of plants can extract suspended water from the soil until the residual water content is reduced to somewhat more than half of specific retention. At least approximately, this limit on the quantity of suspended water available for growth is a characteristic of the particular soil, and does not depend on the species of the extracting plant. It is expressed as the "wilting coefficient," which is the percentage ratio of (1) the weight of water in the soil at the moment when plants growing in that soil first wilt permanently owing to a deficient supply of soil water to (2) the weight of the soil when oven dried.

Evaporation can extract soil water until the residual content is even less than that of the wilting coefficient; specifically, until that residual content is only slightly more than one-third of specific retention. Again, the residual is a characteristic of the soil, which is expressed as the hygroscopic coefficient, or the percentage ratio of (1) the weight of water which at a given temperature the soil will absorb after it has been oven dried and then is placed in a saturated atmosphere to (2) the weight of the dried soil.

With respect to the Pacific Northwest, these hydrologic characteristics of the soil belt enter forcefully into the subject here treated. Over all that region, rainfall during the growing season amounts to no more than a minor part of the water required for the growth of native or crop plants. Accordingly, excepting irrigated areas and low lands along perennial streams or lakes, the suspended soil water generally has been depleted nearly or quite to the wilting coefficient before the first rains of autumn. The resultant deficiency of moisture in the soil belt probably is equivalent to water at least 12 inches deep, and over extensive areas more nearly 18 inches or more deep. Over the extensive semiarid part of the region, that which is east of the Cascade Range, this yearly deficiency in suspended soil water commonly exceeds the yearly precipitation; in consequence only during the infrequent years of uncommonly heavy precipitation is the deficiency fully satisfied and does any water infiltrate beyond the later reach of plants and of evaporation. Even in the subhumid and humid parts of the region, largely west of the Cascade Range, the infiltration of autumn and early winter is expended largely in replenishment of soil water. Until such replenishment is accomplished only a nominal amount of the rainfall may be rejected to overland runoff from the flatter terranes.

Suspended water of the intermediate belt--Little specific information is available as to quantity of suspended water in the intermediate belt, which lies below the reach of evaporation or extraction by plants. Presumably the minimum water content would approximate the specific retention of the materials.

With respect to the subject here treated, the intermediate belt is of interest chiefly as the conduit through which infiltrated water must percolate in order to reach a zone of saturation and later contribute to ground-water runoff. If the intermediate belt is thin or absent, its effect is here negligible. However, if the belt is thick it may detain a considerable quantity of water in

transit to the zone of saturation; accordingly, within it the fluctations in amount of infiltration from year to year may be equalized effectively, so that ground-water runoff becomes fairly constant. In other words, where the intermediate belt of suspended water is thick, a considerable interval of time may intervene between infiltration of water at the land surface and its discharge to the streams as ground-water runoff. A striking example of delayed ground-water runoff, possibly from the cause here suggested, is given later in this report.

Water in the zone or zones of saturation

General features--With respect to the subject of this paper, a zone of saturation is a body of rocks, granular or nongranular, in which the functional openings are completely filled with water under hydrostatic pressure. Only the water of such zones is "ground water" in the sense of this paper.

Zones of saturation are integral parts in the natural drainage system of the land. With few exceptions, they are sustained by infiltration; in part from rain, melting snow, or irrigation water on permeable land surfaces; in part by seepage from streams whose hydrostatic head is greater. Very largely their water is in motion and ultimately is discharged at springs, by the transpiration of certain water-loving plants whose roots tap the capillary fringe of the water table, by seepage into streams whose hydrostatic head is lower, or by seepage into the ocean. In comparison with the lakes and streams of the land surface, the volume of water in such zones of saturation is very large; a body of granular material one sq mi in extent, ten ft thick, and having a specific yield of ten per cent (for "water-bearing" materials, specific yield commonly ranges up to about 35 per cent, by volume) has an effective water-storage capacity of 640 ac-ft; unwatering such a body would sustain a uniform discharge of 0.88 cfs for a year. Thus, within a region as extensive as the Pacific Northwest the aggregate volume of water so stored above sea level doubtless amounts to billions of ac ft. Also, in comparison with streams, the velocity of water movement within a zone of saturation ordinarily is very slow; it is measurable in terms of hundreds of yards a year rather miles an hour.

Where the upper surface of a zone of saturation is in permeable material, that upper surface, a water table, is free to rise as water is added to the zone by infiltration, and to fall as water is discharged naturally or is withdrawn from wells. Here changes in water level measure changes in water storage, and the zone functions as a ground-water reservoir. On the other hand, where the upper surface of a zone of saturation is formed by impermeable material, the water of the zone is confined under hydrostatic head, which commonly is that imposed from an area of unconfined water to which there is hydraulic continuity. Here, in wells tapping the confined water body, changes of water level measure changes in head but not changes in storage; here, the zone acts as a conduit but not as a reservoir (excepting very small changes in storage incident to elastic deformation of the materials as the head changes).

The water body which occupies each distinct zone of saturation is in dynamic balance between replenishment (infiltration) and discharge. Hence, over a term of years or decades, discharge is equal to replenishment and there is no net change of the volume in storage. However, all three variables, replenishment, storage, and discharge, generally fluctuate continually between limits which are characteristic of the particular water body. At one extreme, if the body is of small extent or volume in relation to potential infiltration and discharge, the fluctuations commonly are rapid and the rate of discharge may lag only hours or days behind the rate of infiltration. Such characteristics generally apply to the water in unconfined zones of saturation at shallow depth beneath the land surface, especially to the transiently saturated zones to which reference will be made. At the other extreme, if the body is of large extent and volume in relation to infiltration and discharge, and especially if the principal areas of discharge are remote from those of infiltration, generally the fluctuations are slow and rate of discharge may lag behind the rate of infiltration by years. (A striking example of five-year lag in a certain part of the Pacific Northwest will be introduced.) Such characteristics apply to the water body in the regional zone of saturation, especially where the top of the zone is far below the land surface.

In general, all land areas are underlain by a perennial and regional body of ground water which extends downward as deeply as continuous openings exist in the rocks. Above the regional body, and generally of local extent, one or more distinct bodies may be perched on impermeable material; by definition, such perched bodies are those which are separated from the regional zone of saturation by an intervening zone of aeration. They may exist perennially or intermittently; they have no hydraulic continuity with the regional body. If no perched bodies exist, there is only one zone of saturation and only one overlying zone of aeration, which extends through the soil to the land surface.

The uppermost part of the regional ground-water body may be semiperched, that is, it may have greater hydrostatic head than the underlying part. This condition exists only where essentially impermeable but saturated rocks occur within the regional body, and where the permeable rocks above and below are distinct in terms of the dynamic balance between replenishment, movement, and discharge of water. Here, free hydraulic continuity does not exist vertically throughout the regional zone of saturation.

Transiently perched or semiperched ground water--At any given place, the zone which nominally is aerated and contains only suspended water, is likely to be composed of diverse materials which range widely in capacity to transmit infiltered water downward. If a layer with high transmissibility is underlain by one of substantially less transmissibility, infiltrating water there may be checked and detained in sufficient amount to create a temporary zone of saturation which is perched or semiperched, and so which is not in effective hydraulic continuity with the regional zone of saturation below. Moving laterally above the layer of low transmissibility, water in the zone temporarily saturated would in part reach points of discharge at the land surface, and there would form ephemeral or intermittent springs. Presumably, transient accumulation and discharge of ground water, as here outlined, might take place at any depth within the nominal zone of aeration.

With respect to the Pacific Northwest, the writer concludes tentatively that such transient saturation occurrs rather commonly during severe or prolonged storms, especially where a thick vegetative litter of large infiltration capacity rests on soil much less permeable, and on rugged terranes where a relatively thin mantle of surficial detritus rests on dense bedrock. He also concludes that dissipation of transiently perched water at ephemeral high-level springs probably accounts for a substantial part of runoff during the later part of, and for several days following, a severe storm. In hydrologic analyses, this component of stream flow has been discriminated under terms such as "storm ground-water runoff." The writer does not seek to challenge the propriety of this terminology; however, he desires here to draw the sharp concept that in considerable part this so-called ground-water runoff which can be ascribed to individual storms probably is not derived from the regional zone of perennial saturation.

Perennially perched ground water--Perennial bodies of perched ground water generally exist where the streams, in eroding their valleys, have cut through an impermeable bed into underlying material of greater permeability. Thus, usually these perched bodies are not hydraulically continuous with the trunk streams of a region. Very commonly, however, they afford the source for high-level springs which in the aggregate may contribute substantially to the flow of tributary streams. Their increment to stream flow may or may not be at a steady rate.

Water in the regional zone of saturation--Where it is unconfined, at least the upper part of the regional zone of saturation usually is tributary to certain reaches of the perennial streams on the land surface. Under this condition, at least so long as the stage of the stream is stable or is falling, discharge from the ground-water body enters the stream channel and constitutes a part of the runoff. However, so long as stream stage is rising, the hydraulic gradient between ground-water body and stream may be interrupted, so that ground-water runoff is impounded as bank storage.

Runoff from the regional ground-water body may occur by dispersed effluent seepage along the greater part of the stream, may issue as springs scattered along some certain reach or reaches of the stream, or may be sharply focalized in a single large spring or group of springs whose flow virtually constitutes the stream. As between these modes of discharge, the distinction depends largely on features of land form and geology, which are beyond the scope of this paper. In general, however, this ground-water runoff affords a large part of the dry-season flow in many streams.

Runoff from snow

For the purposes of this paper, and except as a small portion is dissipated into the atmosphere by evaporation, snow may be considered as water which is in dormant seasonal storage on the land surface, and which on melting follows essentially the same hydrologic cycle as that which has been traced with respect to rain (see Fig. 1). However, modifying conditions are introduced by features of climate within the areas of snow accumulation. Thus, at one extreme, if snow does not fall until soil and subsoil have been frozen to considerable depth, and if temperatures remain low throughout the winter, nearly all the snow may later be discharged by overland runoff of its melt water before the soil thaws. Under such conditions there would be little or no infiltration within the snow area during the winter, and the soil-water deficiency of the antecedent autumn might remain as a demand on early-summer rainfall. At the other extreme, if the soil is unfrozen when

snow first falls, and remains unfrozen for an extended period owing to the insulating effect of a thick snow blanket, infiltration might go on through a considerable part of the winter and in an amount substantially greater than that from rain on a snow-free area. Accordingly, other conditions being the same, the amount of melt-water runoff from the snow area might be substantially less but subsequent ground-water runoff more.

Selected features of ground-water runoff in the Pacific Northwest

Runoff derived from bodies of ground water affords substantial increments to the flow of streams in the Pacific Northwest. Outstanding specific examples include (1) the so-called Thousand Springs and other large springs which, along a 40-mile reach of the Snake River below Shoshone Falls, Idaho, discharged somewhat more than 5000 cfs of ground water as of 1918 [MEINZER, 1927, pp. 42-51]; (2) the numerous large springs along tributaries of the Deschutes River in central Oregon, whose aggregate discharge is in the general order of 3000 cfs [MEINZER, 1927, pp. 63-71]; and (3) the Spokane River and Little Spokane River in eastern Washington, which commonly have gained as much as 1000 cfs during the late summer and autumn, from springs within a few miles of Spokane [PIPER and LA ROCQUE, 1944, pp. 89-90]. These examples are outstanding not only in the Pacific Northwest, but also in all the United States.

The proportion of stream flow which is derived from ground-water runoff ranges very widely from one stream basin to another, as is brought out by the graphs of Figure 2. These graphs show the accumulation of the monthly deviation from uniform flow in three selected streams of central Oregon, as follows:

(1) John Day River at McDonald Ferry, Oregon: Drainage area, 7580 sq mi; the gaging station is below numerous small diversions for irrigation, but doubtless is below essentially all the return flow from that irrigation; mean yearly runoff (for the 25 years, October 1, 1920-September 30, 1945), 1,274,200 ac ft or 3.15 inches depth on the drainage area; equivalent uniform flow, 1758 cfs; recorded extremes of flow, 24,900 and four cfs, that is, 1420 and 0.002 per cent of the 25-year mean; as these extremes indicate the stream is excessively "flashy" (even though the measured minimum flow doubtless is moderately less than the natural minimum, owing to depletion by diversions), and perennial ground-water runoff is insignificant in amount.

(2) Deschutes River at Biggs, near Moody, Oregon: Drainage area, approximately 10,500 sq mi; above the gaging station there are diversions for irrigation by five principal canals near Bend and by numerous smaller canals; also, there are several irrigation reservoirs in which, however, the net yearly change of storage is relatively small; probably the greater part of the return flow from the extensive irrigated areas near Bend reaches the river above the gaging station. The sum of (a) the flow measured at the station and (b) the diversions by the five principal canals, taken as a very close approximation to natural flow at the station, yields the following characteristics: Mean yearly runoff, 4,219,600 ac ft or 7.53 inches depth on the drainage area; equivalent uniform flow, 5823 cfs; recorded extremes (gaging station only, canals excluded), 43,600 and 3380 cfs, or 750 and 58 per cent of the 25-year mean. In proportion to drainage area, mean runoff from the basin of the Deschutes River is 239 per cent of that from the John Day. Here the maximum recorded flow is of transient magnitude, as for the John Day basin, owing to large overland runoff. The ratio of minimum to mean, 58 per cent, indicates that among the larger streams of the Pacific Northwest the Deschutes River is uncommonly steady in runoff; this characteristic is an effect of large perennial ground-water runoff, which constitutes essentially all the dry-season flow.

(3) Metolius River at Montgomery Ranch, near Grandview, Oregon; drainage area, approximately 325 sq mi; there is neither diversion from, nor regulation of the river above the gaging station. Flow characteristics are as follows: Mean yearly runoff, 1,023,900 ac ft or 58.50 inches depth on the drainage area; equivalent uniform flow, 1413 cfs; recorded extremes, 5780 and 1080 cfs, or 410 and 76 per cent of the mean. It is noteworthy that drainage area is only three per cent, but mean runoff is 24 per cent of that of the Deschutes River, to which this stream is one of the principal tributaries from the west. In terms of depth on the drainage area, the mean yearly runoff from the basin of the Metolius River is 7.8 times that from all the basin of the Deschutes; probably it exceeds mean yearly precipitation on the drainage area. Here, runoff is uncommonly steady indeed; minimum flow, essentially all of which is perennial ground-water runoff, proportionately is 1.30 times that in the Deschutes and is several thousand times that in the John Day.

These contrasts in the general runoff characteristics of the John Day and Deschutes Basins are all the more striking because the two Basins are contiguous and have about the same proportion of forest cover, also because, excepting the westernmost part of the Deschutes Basin, the two

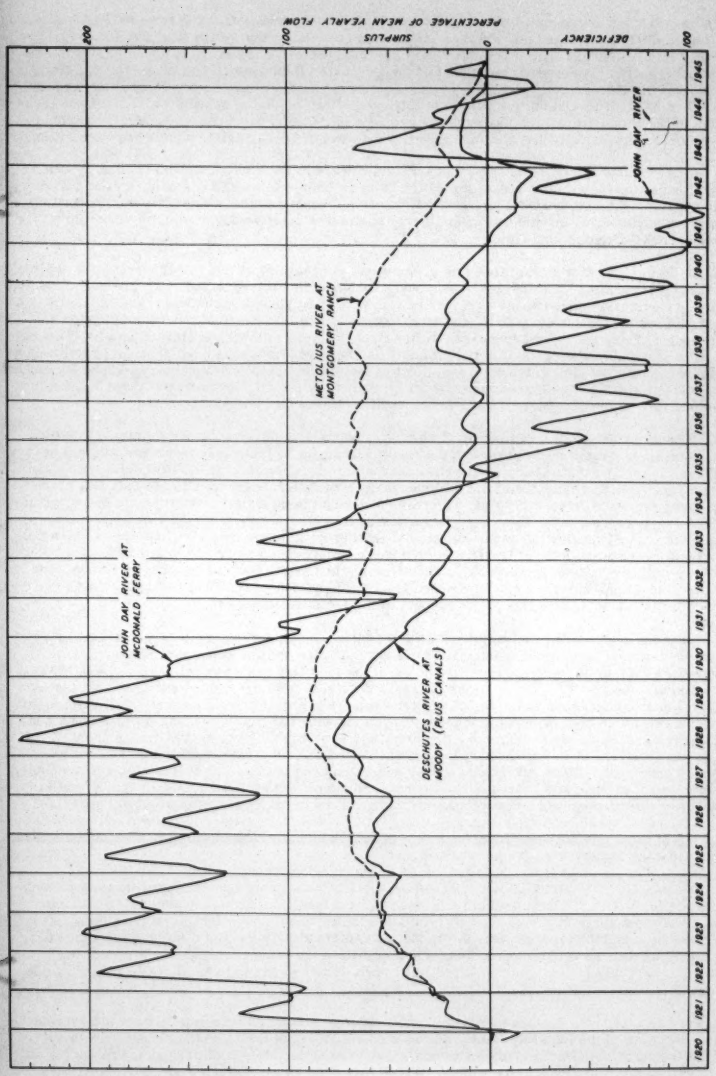

Fig. 2--Accumulated monthly deviations from uniform flow in three streams of central Oregon, in percentage of the mean for the 25 years ending September 30, 1921-1945

Basins are alike in mean altitude, in relief, and in climatic variables. The two are unlike in geologic features which determine their average infiltration capacities; that of the John Day Basin is relatively small, whereas that of the Deschutes Basin (especially certain parts of the Basin) is uncommonly large. The westernmost part of the Deschutes Basin, which has been excepted from certain of the comparisons just made, includes the east flank of the Cascade Range and exceeds the other parts of the Basin in altitude, in total precipitation, and in snowfall; also, it spans those parts of the Basin which probably have the greatest infiltration capacity. Part of this excepted area falls in the Basin of the Metolius River, whose runoff characteristics have been generalized.

In the graphs of Figure 2, segments inclined upward to the right span periods during which runoff exceeded the uniform mean flow of the 25-year base period, and segments inclined downward to the right span periods during which runoff was less than the mean. Uniform inclination indicates steady flow, and amount of inclination measures relative deviation from mean flow. These graphs disclose further:

(1) In the John Day Basin there was progressive decrease of runoff in 1924-1926, and especially in 1929-1931 and in 1933-1936; there was sharp increase in 1921-1922 and 1942-1943. Seemingly, these periods have lagged about a year after corresponding periods of deficient and excessive precipitation, respectively; that is, decrease has continued into the first wet year following a succession of dry years, and increase into the first dry year following a succession of wet years. At least in considerable part, this lag probably has been due to seasonal detention of precipitation in the form of snow, and to the deferred effect of fluctuations in soil-water storage. The lag can not be ascribed in any large degree to perennial ground-water runoff, because the characteristic low summer flow in the stream precludes such runoff in more than a nominal amount.

(2) For the Deschutes Basin, runoff characteristics have differed fundamentally, aside from the much slower rates of increase and decrease. Thus, (a) in 1925-1926 there was a slight net increase in the Deschutes but a substantial decrease in the John Day; (b) in 1932-1936, decrease in the Deschutes was nearly uniform and moderate, whereas concurrently in the John Day there was some increase through 1933 but then there followed the most rapid decrease of record; (c) in 1938-1942, decrease in the Deschutes was again uniform but nearly the most rapid of record, wherease in the John Day the decrease was only moderate through 1941 and then was terminated by sharp increase in 1942. It is believed that these differences are an effect of substantial lag between (a) the perennial ground-water runoff, which has been shown to be large in amount, and (b) the fluctuations in the yearly infiltration from rain and snow. Such lag is demonstrated more forcefully in the next paragraph, with respect to the Metolius River.

(3) In the Metolius Basin, major periods of increase and decrease have lagged at least five years behind the corresponding fluctuations in the John Day Basin. Thus, successively, (a) increase in the Metolius continued until 1928 but in the John Day had ended with 1923; (b) in 1932-1938 runoff from the Metolius remained very near the mean, completely at variance with the John Day; (c) marked decrease in the Metolius began with 1939 and continued through 1942, seemingly to correspond with decrease in the John Day beginning with 1933 and extending through 1936; and (d) slight increase in the Metolius during early 1943 probably reflects heavy overland runoff, but subsequent decrease has continued at the rate of 1939-1942, as though equilibrium had not been reached previously. Disregarding the minor accretions due to seasonal overland runoff, evidently the periods of progressive increase and decrease of runoff in the Metolius Basin are far out of synchrony with fluctuations in precipitation. Because the greater part of the runoff from this Basin issues at a relatively few springs of large magnitude, also owing to geologic and hydrologic features of the Basin not here described, it is concluded that the substantial lag here demonstrated is wholly a lag in perennial ground-water runoff.

The runoff characteristics just derived for the Metolius Basin are not distorted by diversion or regulation within the Basin, and to that extent are natural; possibly they are distorted somewhat from the natural by the effects of infiltration from the extensive irrigation near Bend. For the Deschutes and John Day Basins, the runoff characteristics presented doubtless are distorted somewhat by diversion, regulation, and irrigation within the respective Basins; however, that distortion probably is negligible with respect to relative amount and term of lag in ground-water runoff.

For the Deschutes Basin as a whole, runoff characteristics are a mean between the extreme characteristics of the John Day Basin and those of the Metolius Basin, respectively. From one part of the Deschutes Basin to another, local runoff characteristics doubtless range as widely as these extremes, if not even more widely. Within this wide range, the dominant characteristics are those of the highly permeable areas, even though those areas span only a small percentage of the whole Basin. Of these highly permeable areas, the Metolius Basin constitutes a considerable and representative part.

Bases for forecasting stream flow

Thus far in the Pacific Northwest, forecasting of stream flow has been undertaken with respect to time and magnitude of damaging floods, and to supplies of water potentially available for irrigation. Ultimately, forecasts may become necessary with respect to water available for impounding by all-purpose river-utilization works, to rate of autumn depletion in flow, and to amount of minimum flow for purposes of operating hydroelectric and industrial plants most effectively. With respect to industrial uses, there may be an auxiliary need for forecasting the chemical quality of river water under minimum-flow conditions. These several objectives of forecasting involve distinct techniques.

Of necessity, forecasts of floods depend primarily on adequate climatologic data, antecedent and current, projected into the immediate future. They depend secondarily on hydrologic characteristics of the particular basin under intensive rainfall or excessively rapid melting of antecedent snow. Their reliability is conditioned largely by the accuracy with which the character and duration of storms can be predicted, and on the availability of current reports from climatologic stations and from key gage-height stations on the streams. At this time, further refinement in such forecasts seems to lie in more intensive placement of climatologic and gage-height stations, also in wider use of automatic reporting equipment at outlying key stations.

Forecasts of irrigation supplies have been developed most fully from empirical correlations between (1) the quantity of water stored on the particular basin in the form of snow, at a standard date antecedant to the period of melt-water runoff and (2) the quantity of subsequent runoff, measured at a key-gaging station downstream. In the conventional technique, total volume of water in snow storage is not determined; rather, water equivalent of the snow mantle is measured along a relatively few selected courses, and resultant values are taken as an index to aggregate volume of water in the snow on the particular drainage area. For certain basins, forecasts have deviated substantially from actual water yield; the reasons include the following: (1) The index value of the water equivalent in snow necessarily antedates the melt-water runoff; actual yield of water from the snow-covered area is influenced by interim precipitation and temperature, but at this time these climatic variables cannot be forecast with assurance. (2) Actual yield is influenced by hydrologic characteristics of the drainage area which intervenes below the snow line but above the key-gaging station; potentially, the degree of influence increases with the extent of this area, which commonly is large. These hydrologic characteristics are not weighed in the conventional technique except as mean values enter the standard coefficient of correlation between measured runoff and index value of water equivalent in the snow mantle. (3) Among pertinent hydrologic characteristics, the technique so far developed does not involve values for amount and lag of ground-water runoff which may pass the gaging station during the term of melt-water runoff. For areas such as the Basin of the Metolius River, previously described, the influence of ground-water runoff doubtless is large.

Facilities for improved reliability in forecasting from snow surveys would seem to include, chiefly: (1) More numerous snow courses, for a stronger index to aggregate water equivalent; (2) air-photo reconnaissance, for weighting the index according to extent of the snow mantle, as advantageous; (3) determinations of soil moisture along selected courses, adequate to afford index values for water suspended in the soil zone on the standard date, both above and below the snow line; (4) observation wells located strategically below the snow line and possibly above the snow line, to afford an index value for ground-water storage on the standard date; and (5) a suitable coefficient for the rate of depletion in ground-water storage; that is, to introduce the lag between ground-water runoff and antecedent precipitation, as relevant.

Forecasting into the period of autumn depletion in stream flow is an untried field in the Pacific Northwest. Fundamentally such forecasting must be projected from measured flow on some standard date, according to characteristic rate of depletion from antecedent flow and from antecedent conditions of ground-water storage. If and when the need arises, effective techniques would be available only as systematic observation and analysis of pertinent variables had been continued over an antecedent term of years, preferably at least ten years.

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DISCUSSION

E. N. Peterson (Ebasco Services Inc., Portland, Oregon)--Piper's paper on runoff is a valuable contribution to the science of forecasting seasonal water supplies. It is particularly timely in view of the present power shortage and the important role that forecasts play in predicting available power resources in the Northwest. This discussion is intended to point out how and to what extent reliable runoff forecasts would be of benefit to the Northwest Power Pool.

The Northwest Power Pool (NWPP) includes the area comprising the drainage basin of the Columbia River within the United States and in addition the drainage areas of Salt Lake, the Upper Missouri River, and the Pacific Northwest coastal rivers. There are 11 utilities which constitute the membership of the NWPP and these represent the major systems in Idaho, Utah, Montana, Washington, and northern Oregon. Eight of these are private utilities, two are municipally owned, and one is federally owned.

During the latter half of 1946, the load in the NWPP grew very rapidly and unexpectedly. The December peak load was 3,179,000 kw as compared with 2, 547,000 kw the year before, a growth of 25 per cent. The average 1946 load was 1,850,000 kw and for December it was about 2,300,000 kw, or 500,000 kw more than the previous December. Almost 99 per cent of the 1946 load was carried by hydroelectric power and only one per cent came from steam power plants. Had 1946 been a critically dry year instead of a fairly wet one, the steam generation would have been greater. But the total steam capacity is only 400,000 kw out of a total Pool capacity of 3,500,000 kw, or slightly over ten per cent.

The 11 utilities in the NWPP are interconnected by transmission line ties or networks and operate as a single system. The main objective of pooled operation is to obtain maximum and most economical utilization of all resources and facilities in the area regardless of ownership. All power resources in the region are thrown into a common pool. Insofar as physical limitations permit, facilities in one area such as generating plants, reservoirs, transmission lines, are available for use in other areas within the Pool. Such a cooperative venture naturally requires a central clearing house and this is the function of the Coordinating Group of which the writer is a member.

Importance of runoff--Hydroelectric resources are composed of two elements, one known, the other unknown. Storage in reservoirs is the known element since the water in a reservoir can be converted into a definite amount of energy on the basis of plant capacity and operating experience. Future stream flow or runoff is the unknown or at best it is known only within very wide limits. In 1946 energy from storage constituted only three per cent and from current runoff 97 per cent of the total hydro generation. If the year had been a critical one the storage component might have amounted to some eight per cent of the total.

It might be inferred from this that stored energy plays a very unimportant part in the economy of the power pool. This is not true. Careful planning in the most economical utilization of storage water, so as to produce the maximum load carrying ability at the time when stream flows are at a minimum, makes the storage reservoirs strategically very important. This will become evident by referring to the chart (see Fig. 3) which I shall discuss a little later on.

From the above, it is seen that over 90 per cent of the power resources in the Northwest come directly from current runoff. Consequently, any reliable prior knowledge of runoff, particularly during the low water period from July through March, is valuable information for those responsible for the coordination and operation of the utilities in this area.

Operating program--Since 90 per cent of our resources depend on future stream flows which are largely unknown, how can the Northwest Power Pool be sure to carry its load? A fundamental precept of any electric utility is that it must always be ready to serve. Any time, day or night during drought or during flood that a customer elects to close a switch, the utility must be ready to carry the load thus thrown on to its system.

The answer to the above question is that the load is carried on the basis of an overall plan prepared one year in advance, a plan setting up for each utility its operating procedure insofar as such procedure affects the loads and resources of the Pool. This plan is called the Operating Program. Since the low-water period in the year begins generally in July (except for the Columbia River plants where the low-water period begins later) the operating year starts in July and ends in June. In order to have it available in time, the Operating Program must be prepared in the spring and available to the operators before July 1.

This means that, not only must load estimates be prepared a year in advance, but estimates of resources must be made and particularly estimates of runoff throughout the first nine months of the operating year. Now it is usually possible, though not always, to estimate loads within a reasonable degree of accuracy, particularly for systems that have been in operation many years. Also, we know definitely what resources we have stored in the reservoirs of the Pool as well as how much steam power we have available. But this represents only ten per cent of the total and the present state of the art does not enable us to forecast with any degree of accuracy the other 90 per cent representing the resources that will be available in the form of runoff.

In order to set up a watertight program, we are compelled to assume that the runoff in the period ahead will be very low, as low in fact as it has ever been in the past. This is admittedly a very pessimistic assumption and the probability of such a condition occurring is slight. It would be highly desirable to find a way to permit the use of some other assumption.

Having determined what is the worst water year of record for the Pool as a whole, we make the assumption that the year ahead will not be worse than that. If it should be worse, we can probably still carry the load, but at the expense of much pain and sleeplessness. Pooled operation derives great benefit from its ability to take advantage of diversity, particularly diversity in runoff. Critical low-water conditions may exist, say, in Washington but across the mountains in Montana or in the Salt Lake area or Snake River Basin the runoff is likely not to be critical. Thus the water deficiency in one area is made up from water surpluses in the other areas by energy transfers over the transmission network.

Master chart--Reference is made to Figure 3, commonly called the master chart. It is the frontispiece of our Operating Program for 1946-1947 and represents the summation of all the planning, scheduling, and estimating that have gone into the preparation of that program. The chart is changed every year as loads change and resources are increased through additional power plant construction. Half of the chart is devoted to average loads and resources and half to peaks. I shall discuss only the left half dealing with averages. The heavy, wavy line is the estimated load which rises in January to a little less than 2,000,000 kw. The chart was prepared in the spring of 1946. When January 1947 came around, the actual average load in that month was about 2,400,000 kw, almost half a million kw more than the estimate. However, the fact that the increased load was carried indicates that there is great flexibility in pooled operation. It also indicates that there was considerable surplus available.

The chart shows graphically the important part played by natural stream flow or runoff in the setup of total available resources. The bottom area is the output from natural stream flow under critical water conditions and its distribution by months. In general it drops from July through January, whereas the load tends to rise during that period. In large measure the topmost shaded area also represents potential output from natural stream flow which, with the estimated load shown, would have been nonusable but which, in view of the high actual load, turned out to be not only usable, but most welcome.

The storage draft, another shaded area, is fitted in on top of the usable stream flow so that the total hydro energy generation (natural flow plus storage) follows quite closely the shape of the load. It is seen that at the end of January the natural flow produces 1,200,000 kw and the storage draft about 600,000 kw or a total of 1,800,000 kw. This indicates that storage, in spite of its small aggregate percentage of the whole as shown by the relative areas, plays an important part in the total kilowatt load that can be carried.

A new operating program and a new master chart are now in preparation for the 1947-1948 operating year. It might be of interest to mention that the top line on the chart here presented, representing total average resources of the Pool, will be raised only slightly in the new chart. On the other hand, the estimated 1947-1948 load is up so far that in places it virtually coincides with the total resources. Under these circumstances, surplus will be largely nonexistent.

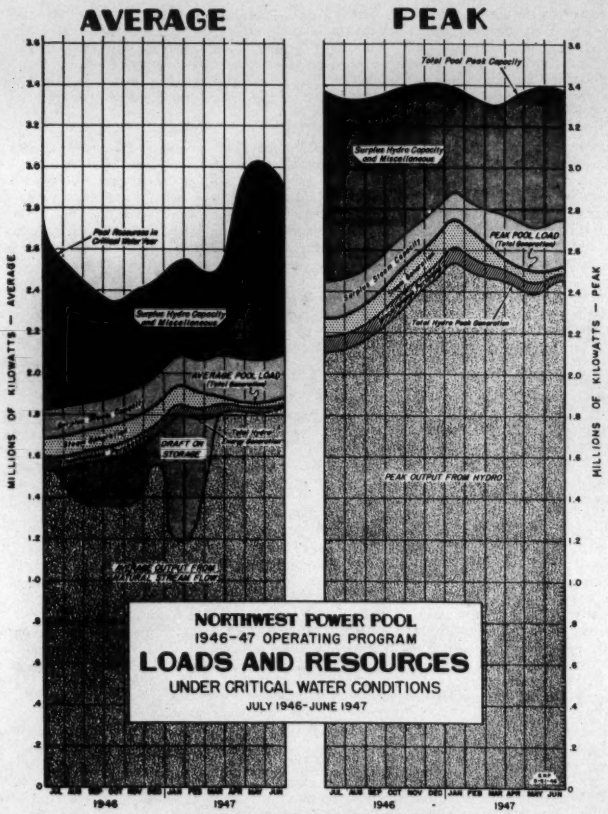

Fig. 3--1946-1947 operating plan.

Operation of reservoirs--The Operating Program is a rather complicated and detailed job and it has many uses. One of the most important of these is the setting up of time schedules of reservoir operations, commonly known as rule curves. These pertain only to the reservoirs containing seasonal storage and there are 21 of them widely distributed throughout the area. The rule curves indicate what the elevation of each reservoir should be at any given time during the drawdown period.

Setting up rule curves almost a year in advance is not a simple task. The fundamental objective is simple enough, namely to leave enough usable storage in the reservoirs at any time so that resources will be adequate in case of critical water from then on. Of course economy prescribes that reservoirs should be empty at the end of the dry season as that will assure minimum fuel consumption, but this is generally hard to do in any year except a critical one. Many factors enter in to affect the rate at which reservoirs may be drafted. Among these are limited downstream generating capacity, desire to keep a reservoir level high to avoid loss of peaking capacity,

physical or legal controllability of the reservoir, need to provide storage to mitigate floods, need for energy reserves, physical limitations, ice conditions, and many others. Perhaps to these might be added one more, definite knowledge of forthcoming runoff, but that may be looking too far ahead.

A number of reservoirs in the NWPP, particularly in the eastern group are used for both power and irrigation. Irrigation requirements have a higher priority than power requirements since a person can dispense with light more easily than with food. In such cases drafting reservoirs for power purposes can be done only to the extent that this does not interfere with irrigation requirements.

In some cases, water discharged from reservoirs passes through a series of power plants before reaching the irrigation canals. This is true of Bear Lake in Utah. In the case of the American Falls Reservoir in Idaho, 97 per cent of the primary storage water is diverted for irrigation before reaching a number of power plants downstream.

Generally speaking, water diverted from hydroelectric plants must be replaced by steam generation resulting in the burning of precious fuel. One acre foot in Bear Lake can produce as much energy as 3/4 ton of coal. On this basis the lake contains the equivalent of a million tons of coal. This simply indicates the need for maximum economy on the part of irrigators as well as others in the use of water. Wasteful use of irrigation water may mean waste of an exhaustible natural resource.

In the coordinated operation of reservoirs, the power systems have learned to "transfer" water from one watershed to another and perhaps very distant watershed. This is not literally true, but by drawing heavily on the reservoir where water is plentiful and converting this water into energy, it is possible to reduce drafts on another reservoir which perhaps is having a drought, thereby permitting it to return to normal. In the same manner it is possible to generate steam energy and "store" it in a reservoir.

Forecasts of stream flow--When the winter snows are gone and the critical fall and winter months come, runoff depends to a considerable extent on drafts from ground water. Piper estimates that there are billions of ac ft stored in the ground above sea level and he intimates that long-term ground-water records at strategic locations would permit reasonably accurate forecasts of what the minimum flow might by during the fall months. This is what the NWPP lacks; therefore it is compelled to use the pessimistic assumption of lowest recorded flow.

It is probable that the critically low autumn and winter runoff in most cases results from a combination of circumstances including low precipitation occuring after a long period of ground-water depletion. There is undoubtedly a relation between ground-water levels and the rate at which ground water is discharged into streams, and long-term records would probably make it possible to establish that relation. If so, one could assume minimum precipitation and still have the assurance that the fall runoff would be very different from the historical minimum. This would be a big forward step in improving the economy of hydro operation.

Some steps have been taken towards gathering records on ground water through the Subcommittee on Hydrology in the Columbia Basin Inter-Agency Committee. These steps apparently do not contemplate making use of a source of information which is probably available from the utilities comprising the NWPP. They have or can obtain much information with regard to past and present ground-water levels which might do much to shorten the long period of waiting before the required records become available.

In the meantime, we might look at the short-term picture and inquire if forecasts which lack the knowledge of ground-water conditions and their effect on stream flows, and forecasts which can offer little definite information as to the monthly distribution of runoff in the fall and winter, are of value to the power systems. They are of value, but to a smaller degree. Runoff forecasts indicating the total amount of runoff in a 12-months period give assurance or otherwise that reservoirs will refill in the spring. Some reservoirs always fill again but others sometimes do not and this may indicate serious conditions in the subsequent dry months.

Short-term forecasts, particularly if they are pessimistic, give us warning to put our steam plants into shape for operation and to look to our fuel supply. However, under recent phenomenal load-growth conditions, most of our steam plants are kept working.

Generally speaking, a forecast of unscheduled total annual runoff is of minor value. The heavier flows may come early when reservoirs are full and the extra water cannot be stored. Or they may come too late to prevent premature emptying of the reservoirs. A time table of stream flow is needed.

Critical low water occurs very rarely. Year after year, utilities, lacking the timetable mentioned above, fail to utilize the energy in their reservoirs for fear that critical water conditions might occur. As a result, when the spring floods come there may be hundreds of millions of kilowatt hours remaining in storage which are completely useless, but which might have been utilized if more definite knowledge of stream flows had been available.

Piper says, "Forecasting into the period of autumn depletion in stream flow is an untried field in the Pacific Northwest." And yet this is really the kind of forecasting that the NWPP requires. In the fall, stream flow depends largely upon rainfall and ground water and this is when our operating problems really begin. Piper has set forth the elements involved in such forecasting. The problem is clearly defined and a modus operandi suggested. A twenty billion kilowatt-hour industry has been asking for it for years. What are we waiting for?

Resume--In this discussion I have tried to bring out that:

(1) Over 90 per cent of the power developed by the NWPP come from natural runoff.
(2) Lacking knowledge of what the runoff will be, it is assumed that the most critical flow of record will recur.
(3) Forecasts of total annual runoff without breakdown by months are of only minor value.
(4) In the critical fall and winter months, runoff consists in large measure of drafts from the immense ground-water reservoir.
(5) Quantitative knowledge of the effect of ground water on stream flow would eliminate perhaps the greatest unknown in predicting fall runoff.
(6) Such quantitative knowledge is obtainable and should be obtained in cooperation with the utilities in the NWPP.

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SNOW-LAYER DENSITY CHANGES

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Abstract--A 25-foot square area of snow pack near Crater Lake, Oregon, was studied systematically during the 1940-1941 season. By successive excavation and refilling of portions of the study site, and by means of identifying ribbons, the metamorphosis of each layer of the snow pack was observed at regular intervals during the accumulation and melting seasons. Observations and conclusions are given regarding changes in density, mass or water equivalent, water storage, water transmission characteristics, and melting rates of the snow. Many of the results confirm existing knowledge and belief on a quantitative basis. Other results, which may be new to many readers, add to or modify well-established opinions. An example is the lack of relationship between the density of snow layers and the weight of the overlying snow.

This paper is a partial summary of work cooperatively conducted by the United States Soil Conservation Service, Oregon Agricultural Experiment Station, Corvallis, Oregon, and the United States National Park Service. It is presented for publication as Technical Paper No. 507, with the approval of the Director, as a contribution of the Oregon Agricultural Experiment Station.

In forecasting the stream flow to be expected from a measured snow supply in any given year, forecasters frequently speculate as to the effect of snow structure and texture upon water-accumulating capacity and water-releasing speed of the snow pack. There is question as to why a greater water yield is secured some years than others from approximately the same volume of mountain-stored snow.

To secure data bearing on these and other questions, an experiment was initiated at Crater Lake National Park, Oregon, in 1940. The experiment was continued in more elaborate form in 1941, but was suspended after beginning of the War. Insufficient funds and personnel shortages have prevented its resumption, but some results of the 1940 work are related in this paper.

Experimental procedure

Location--The experiment site was near Park Headquarters, at elevation 6450 ft, latitude 42°53'48"N, longitude 122°08'12"W, 150 yards west of the outer base of Crater Lake rim. This location, in an open clearing 110 ft south of the all-year highway, was shielded on the south and east by a dense hemlock-lodgepole pine forest, the nearest trees being 120 ft south of the experimental area, and on the west by open timber. Surface of the pervious pumice soil sloped slightly to the south and west. Figure 1, depicting the plot location and the position of contours of stored snow water in the surrounding snow field, as of March 3, 1941, shows that the plot was unaffected by highway snow removal or by undue snow drifting or melting.

Preliminary preparations

Guyed poles at the four plot corners supported a single No. 9 wire that fenced the 25-foot square area, as shown in Figure 2. The wire was raised or lowered from time to time so as to remain about waist high above the snow and warn random skiers. It was more useful as one of the base references for all measurements. A drop of solder on the wire at each corner post provided a means of avoiding lateral shifting of the wire whenever it was raised or lowered to compensate for changing snow level. Chalk lines were stretched both ways across the plot from metal reference tags soldered to the perimeter wire and then plumbed from their intersection to the snow surface, as shown in Figure 3. By this means any particular boundary of excavation, line of cellophane, or point of sampling could be determined quickly and accurately. As far as could be observed, neither the single wire nor the slender corner poles had any drift fence effect, nor did their shadows affect the snow cover.

The intention was to level the entire plot so that parallel ground guide rails, to which all snow-depth measurements were referenced, would be level and flush with the ground surface. Other field activities prevented performance of that work until November 8, 1940. Upon reaching the

experimental plot at that time, the writer found the ground covered with 30 inches of snow. The original plan was thereupon modified to this extent: 2 1/2 inch by 3 1/2 inch guide rails, spaced 61 inches outside to outside, were laid on edge parallel to and with their lower surfaces on the ground surface. The top of each guide rail was thus 3 1/2 inches above the ground surface.

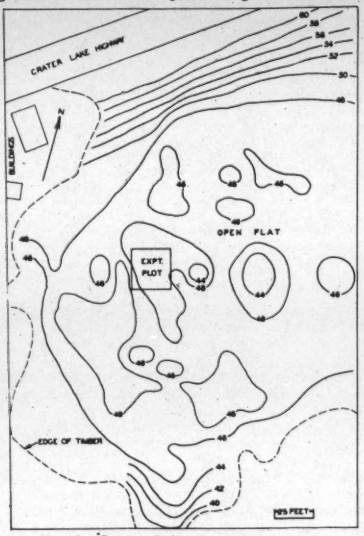

Fig. 1--Crater Lake experiment area, snow-stored water contour

The rails ran approximately north and south with the center of the space between them, called the "work chamber," coincidental with the approximate north and south plot axis. In placing the rails, little snow was disturbed between them, and snow blocks to be sampled were left completely undisturbed. After the rails were laid, the snow trenches were backfilled with snow, but were not foot tramped. The snow blocks west and east of the work chamber were designated W and E, respectively.

Bi-weekly excavation--The central work chamber was not completely excavated at each sampling; rather the excavation was from the south toward the north only within boundaries specifically allotted for each sampling. In no case was this work chamber less than 61 inches wide nor less than 36 inches long. (In the 1942 work, excavation was from north to south so as to shade the working face of the trench.) Snow excavated each time was thrown southward on a snow dump, as shown in Figure 2. Succeeding bi-weekly snow samples were always taken in undisturbed snow, 18 inches ahead of the last old samples and 12 inches ahead of the last excavation. After each set of observations, the central work chamber was immediately refilled with snow that had come from it, and foot tramped to approximate the original condition. On December 23, it was noted that dirt from beneath had become mixed with snow in the work chamber. Because the small clods tended to absorb heat and induce melting, all this snow was hauled away and clean snow was imported to replace it. Special care thereafter was taken to avoid snow contamination in the work chamber.

Lateral sampling--Bi-weekly lateral snow density measurements began November 14, 1940, and ended June 2, 1941, at locations in Blocks E and W, progressing northward from the south reference wire in 18-inch increments at each sampling. The first samples under the south wire were taken at the mid-point between the snow surface (as it then existed) and the top of the guide rails. This layer was called A. Succeeding two-week snow layers were designated B, C, and so on. The height of the ground guide rail was always added in determining thickness of A layer and total snow depth. Succeeding lateral samples in each snow layer were taken in the same plane as the original sample but did not always come at each layer's mid-point, owing to unequal snow settling either above or below the original mid-point. Sampled snow faces in blocks E and W were perpendicular to the ground guide rails, as shown in Figure 4, and lateral samples paralleled the ground surface at right angles to the guide rails. Duplicate samples in each layer were taken each sampling date, one in Block E and one in Block W.

The sampler devised for securing complete snow cores without the digging of secondary trenches is described by WORK, CHILDRETH, and FROST [1944]. This instrument, called the "Crater Lake lateral snow sampler," was used for all horizontal samplings on and after December 9. It is shown in Figure 5

Lateral sample holes were backfilled with lightly tamped snow cores (see Fig. 6). A strip of colorless cellophane one inch wide, to which was tied an identifying tag, was tamped into each hole with the cores. It identified each old hole and provided a means for following the rate of snow settling and for sampling the same section of each snow layer at subsequent dates. Cellophane

Fig. 2--Crater Lake experimental plot, February 3, 1941

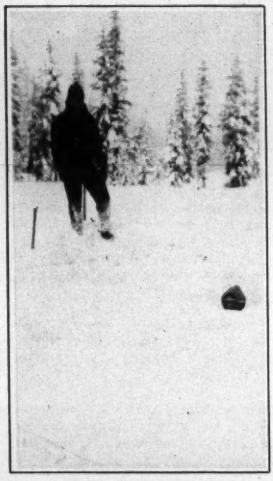

Fig. 3--Crater Lake plot, January 6, 1941; note chalk lines from reference wire

Fig. 4--Work chamber excavation of February 3, 1941; sampler being driven into east face; note cores for back-filling hole piled in foreground

was used in the belief it would not absorb heat and thereby change its position in the snowbody. Its flexibility was also believed important as offering little resistance to any uneven snow settling. Three types of cellophane were used. The first, ordinary colorless, lightweight cellophane used in the samplings of November 14, 28, and December 9, became brittle and was easily broken when frozen. Heavier cellophane was used on December 23, but beginning on January 6, moisture-proof cellophane was used (Blake, Moffit and Towne, No. MPFFBU). This latter cellophane was fairly tough and did not yellow with age.

Snow-layer identification--In order most closely to follow changes of structure and texture in the snow pack, each two weeks' snow deposit was identified by one-inch cellophane strips extending between certain points across the snow surface. These were suitably tagged at the west and east face of the work chamber each measuring date so they could be identified thereafter. The thickness of and rate of settlement of each snow layer was thus measured bi-weekly.

Vertical sampling--Total water content of the entire snow column for each sampling date was determined from duplicate vertical samples taken near the west and east plot boundaries. These holes were also backfilled with tamped snow cores.

Water content of each snow layer also was measured, beginning March 3, by duplicate samples taken vertically in undisturbed snow at the north end of the work chamber in the following manner: A thin, narrow wooden paddle was pushed 14 inches into the snow face on the horizontal plane between bi-weekly snow layers. The snow sampler was set ahead 10 inches from the trench face and thrust downward from the surface to the bottom of the first layer; that is, to the paddle as shown in Figure 7. Snow surrounding the sampler was dug away and the sampler was then removed and weighed. The paddle was next moved to the bottom of the layer below and the procedure continued until all bi-weekly layers were sampled. This differed from ALPS' [1922], method in which density of layers always 12 inches thick was determined at irregular intervals.

Snow temperatures--Duplicate readings of snow temperature referenced to the original midpoint of each layer were made with a long-stem mercury thermometer, bi-weekly, beginning February 17, 1941. The bulb was inserted ten inches into the snow and readings were made with the thermometer in place. The thermometer was checked against one of known accuracy at the beginning and end of the season.

Soil temperatures--Soil temperatures one and one-half inches below the surface were taken with the same thermometer at bi-weekly intervals, beginning February 17, 1941. Ground freezing, or ice on ground, was observed bi-weekly, beginning November 14, 1940.

Snow morphology--Observations of depth and thickness of ice lenses or layers, size and arrangement of ice crystals, and other similar data, were taken on the north face of the work chamber at irregular intervals.

Climatological data available

A climatological station of the United States Weather Bureau was located at the same elevation, 400 ft northwest of the experimental plot. The following daily observations were available there through the entire experiment: (1) Precipitation (inches), (2) snowfall (inches), (3) depth of snow on ground (inches), (4) maximum air temperature (°F), (5) minimum air temperature (°F), (6) prevailing wind direction, (7) character of day (sunrise to sunset), and (8) miscellaneous phenomena.

Records additional to these were secured immediately adjacent to the experimental plot as follow: (1) Daily hygro-thermograph records from November 15, 1940 to June 9, 1941, (2) semi-daily to bi-daily anemometer readings from January 4, 1941 to June 9, 1941, and (3) prevailing wind direction.

A Weather Bureau fruit-frost type shelter on a vertically adjustable frame housed the hygro-thermograph. A slat grill replaced the hardware cloth bottom. The instrument was housed in a "rat cage" of very fine mesh brass screen to prevent snow blown into the shelter from resting on the humidity element. The shelter bottom was continuously about 30 inches above the snow surface.

The anemometer, on a vertically adjustable arm, was offset two ft from its supporting pole, as shown in Figure 8. The cups remained about 18 inches above the snow surface most of the time.

Results

Accumulated daily precipitation compared with snow-stored water--The initial ground covering of snow occurred in 1940 on October 28. Snow disappeared from the plot ground surface on June 9, 1941, and snow-stored water again became zero. Fluctuation of snow-stored water compared with accumulated daily precipitation in the intervening 225 days is shown in Table 1 and Figure 9.

Accumulated precipitation and snow-stored water were approximately equal on November 14. By November 28, snow-stored water equalled only 83.4 per cent of the accumulated precipitation. It appears that between November 14 and 28, with a snow layer on the ground ranging from 28 to 36 inches in depth, 1.6 inches of rain, less evaporation, passed through the snow. Lateral density of snow layer A increased during this period from 23.7 to 33.4 per cent. This was a measure of the settling that occurred, but mean density of the entire column increased only from 27.9 to about 29.4, thus showing that total water content of the A layer was insignificantly increased by the rain.

Fig. 5--Crater Lake lateral snow sampler

Fig. 6--Back-filling lateral sample holes, May 26, 1941

Fig. 7--Showing method of vertical layer snow sampling, March 3, 1941

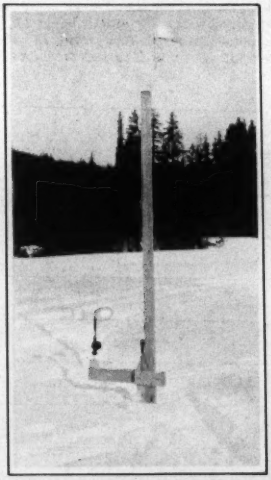

Fig. 8--Anemometer installation, February 3, 1941

Table 1--Comparison of accumulated precipitation and snow-stored water at Crater Lake Oregon, 1940-1941

Date	Accumulated precipitation	Snow-stored water	Ratio
	in	in	pct
Oct. 27	0	0	....
Nov. 14	7.96	8.15	102.4
Nov. 28	9.89	8.25	83.4
Dec. 9	11.83	9.70	82.0
Dec. 23	18.99	16.20	85.3
Jan. 6	25.55	25.05	98.0
Jan. 20	31.54	34.15	108.3
Feb. 3	36.93	40.10	108.6
Feb. 17	39.62	42.70	107.8
Mar. 3	42.19	45.50	107.8
Mar. 17	42.43	44.30	104.4
Mar. 31	44.13	45.20	102.4
Apr. 15	48.31	47.20	102.4
Apr. 28	48.66	42.60	87.5
May 13	53.63	35.45	66.1
May 19	54.60	30.15	55.2
May 26	55.09	17.70	32.1
June 2	56.58	11.25	19.9
June 9	57.94	0.00	0.0

Between November 28 and December 9, approximately 0.5 inch of rain, less evaporation, passed through the snow to the soil beneath. After December 9 and until about March 31, it appears that most of, if not all, the precipitation was stored as snow or in the snow.

After March 31, precipitation accumulated more rapidly than snow storage, so there either was movement of water through the snow to the soil or snow surface evaporation greatly increased. Judging from snow-surface evaporation values furnished by BAKER [1917] and HORTON [1914], there is little possibility of the difference being due entirely to evaporation. After April 15, there was no further accumulation of snow, but rather a loss which accelerated when air temperatures were much above freezing.

On February 17, 1941, it was noted that snow-stored water exceeded accumulated precipitation; this had been the case since January 15. Several reasons might have accounted for the difference, but one most obvious possibility was a leak in the rain gage. A leak was found and repaired on March 1, 1941. Consequently, accuracy of the precipitation record prior to March 1 is open to question, as sometimes the gage may have leaked (with precipitation as snow) and at other times, not (with precipitation as snow). Since careful testing was required to find the leak, it is probable that the leaky gage did not greatly impair the record prior to March 1.

Snow-stored water reached its maximum about April 15. Between April 1 and 15 the increase in snow-stored water was small, being 2.0 inches, or 4.4 per cent greater than on April 1. From the standpoint of advance forecasting of runoff by snow surveys, the customary April 1 final survey date applied to this area was therefore, for all practical purposes, satisfactory in 1941.

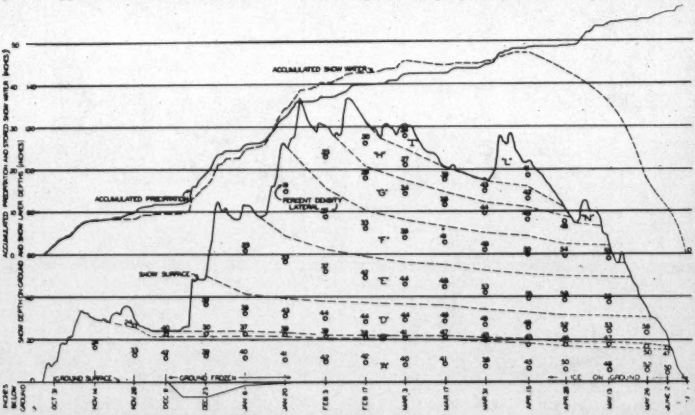

Fig. 9--Snow-layer density changes, Crater Lake, 1940-1941

After April 15, accumulative precipitation, of course, continued, but the water left the snow at a rate generally accelerated with time and decreasing snow depth (and generally increasing daily mean temperature). This differed from CLYDE'S [1931] results, for he found in working

with snow of moderate depth in Utah that the water left the snow at a uniform rate after melting began. However, Clyde's principal water loss period extended over only 16 days, while at Crater Lake in 1941 the period of snow-water loss (of like magnitude) covered 54 days, with more or less upward progression of daily temperatures as the water left the snow.

Total snow depth compared with total snow-stored water--Beginning October 28, with the season's first permanent snow cover, the snow depth gradually increased to its peak for the season on January 25, with marked increases and temporary recessions in depth, as shown in Figure 9. In the same period, accumulated snow-stored water showed coincidental increases but no decreases. Furthermore, since the amounts of accumulated precipitation and stored snow water between December 9 and January 25 were in fair agreement, it may be concluded that depth recessions in the snow surface were caused solely by snow settling and not by melting; that is, not by actual water loss from the snow. After January 25, and until the snow was gone, the snow depth gradually decreased although showing occasional increases because of new snow deposition. The decreases in depth during the latter period, and particularly after March 3, were due less to settling than to actual melting away of the surface snow.

It is well known that snow-water content cannot accurately be estimated from depth measurements alone. The fact that water stored in the snow increased from about 38.5 inches on January 25, to 47.2 inches on April 15, whereas snow depth decreased from about 133.0 inches to about 104.0 inches during the same period, substantiates this statement.

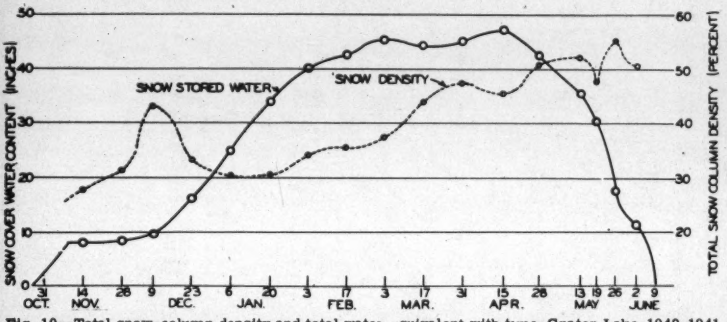

Fig. 10--Total snow-column density and total water equivalent with time, Crater Lake, 1940-1941

Total density compared with total snow-stored water--Total snow-stored water and total snow-column density, based on bi-weekly duplicate vertical samplings along the east and west plot edges, are shown in Figure 10. There is little similarity between the curves. Each fall of new snow increased the total snow water content, but, being of lighter density than the older snow, it had the effect of decreasing the total snow density. A total density decrease is shown from December 9 to 23, whereas the water content definitely increased. A significant water-content increase between January 6 and 20, is associated with a total density change of zero. Figure 10 is therefore shown to emphasize the extreme difficulty of estimating density (or water content) from any depth-time relationship.

Toward the right of Figure 10 note that snow-stored water decreased beginning April 15, yet total snow density continued its upward trend. This differs from CLYDE'S results [1931], for he reported a total density decrease from maximum when melting began; but it agrees with the results of ALPS and ASSOCIATES [1920, 1922] who conducted a study somewhat similar to the one now reported, at Summit, California, in 1916-1921. Clyde was working with snow of only moderate depth, while Alp's conditions were similar to those at Crater Lake; that is, they represented snow of depths greater than those encountered by Clyde.

The sharp density reduction on May 19, is believed due to the cold weather of May 18 and 19, which temporarily stopped snow surface melting but possibly had no effect on drainage of the water out of the under-surface snow. CLYDE [1931] observed this phenomenon in his Utah experiments and was the first to offer an explanation of snow-density decrease during melting.

Table 2--Lateral density of each snow layer as measured in experiments at Crater Lake, Oregon, 1940-1941

Layer	1940				1941											
	Nov. 14	Nov. 28	Dec. 9	Dec. 23	Jan. 6	Jan. 20	Feb. 3	Feb. 17	Mar. 3	Mar. 17	Mar. 31	Apr. 15	Apr. 28	May 13	May 26	June 2
	pct	pct	pct	pct	pct	pct	pct	pct	pct	pct	pct	pct	pct	pct	pct	pct
A	23.7	33.4	41.8	39.4	39.8	41.2	42.4	42.2	40.0	40.6	37.6	45.2	48.9	48.3	51.6	49.8
B		24.2	40.0	30.0[a]	36.9	39.4	39.0	39.4	41.4	46.7	43.4	42.7	44.8	46.9	50.0	47.2
D				32.6	37.9	42.6	43.9	44.2	43.7	46.0	48.3	48.2	51.5	52.8	56.1	...
E					22.9	32.7	37.2	41.6	44.4	48.3	52.6	55.2	58.2	55.9	...	...
F						19.3	27.3	32.8	37.6	40.6	48.0	49.7	54.1	53.3	...	...
G							22.6	28.4	33.9	38.4	44.4	44.9	47.8	...	...	...
H								19.8	26.7	37.9	43.4	41.8	...	...	...	...
I									24.0	...	...	...	...	...	...	...
L												40.6	...	...	...	...
Weighted density of A plus B[b]									40.1	41.2	38.2	44.9	48.4	48.1	51.4	49.5

[a] Believed inaccurate as tube went upward into D layer when sampling east side.
[b] For comparison with vertical density of A plus B. (A was given weight of 8 and B weight of 1.)

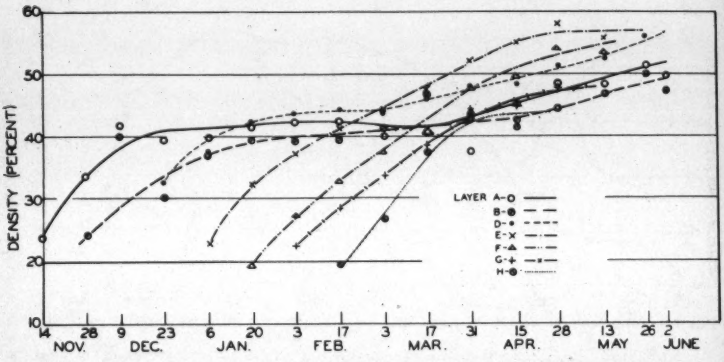

Fig. 11--Lateral density of each snow layer at original mid-point with time, Crater Lake, 1940-1941

Association of layer densities with time intervals--Lateral density of each layer's mid-point, as determined at the first sampling after its deposition and bi-weekly thereafter until the layer's mid-point disappeared, is shown in Table 2 and in Figures 9 and 11. In Figure 11, density is plotted against calendar dates by means of smoothed curves. Results of point-to-point plotting of the data were not considered significant.

It should be noted that snow layers A and B, oldest in origin, were among layers attaining the least maximum density, and layers deposited in mid-winter (D, E, and F) attained a greater maximum density. Morphology observations showed the A and B layers to be of coarse, granular texture after December 9. The percentage of voids between crystals would be then much smaller than that in layers D, E, and F, and the volume of any free water adhering to the ice crystals as a capillary film would be less than that of the finer-textured snow above them. Less interstitial water in A and B layers accounts for the lesser density found in these layers. Careful observations supported this theory; they showed layer D to be less granular than either A or B, but more granular, that is, coarser of texture, than either E or F; also that the mature density of D was approximately midway between that of A and B and the upper layers. Original opinion of these experimenters, that snow of greatest density would necessarily be found in the lower levels, was not verified.

The curves slopes representing the period between March 3 and 17 (see Fig. 11), suggest that time elapsed since deposition has bearing on the rate of density increase. In general, the more recently deposited layers showed the greatest rate of increase. In other words, density of new snow may be expected to increase more rapidly in any given time period than that of older snow.

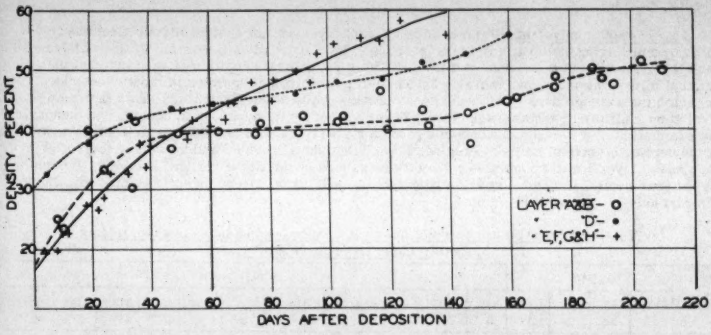

Fig. 12--Snow layer lateral density increase at original mid-point in relation to time at Crater Lake, under climatic conditions prevailing there in 1940-1941

Accordingly, Figure 12 was prepared to show snow density plotted against elapsed time since deposition. The differing slopes of the curves in this figure disclose that there was no constant relation between density and time for all snow layers. Layers A and B are similar enough to be represented by one curve. Initially, these two layers increased in density the most rapidly of any. After about 40 days from time of deposition they increased in density at the slowest rate per day of any of the layers. However, about 150 days after deposition, appreciable melting started and rate of density increase of A and B again went up.

Layer D initially increased in density at nearly the same rate as layers A and B. After about 40 days, however, the density increased more slowly although not so slowly as in layers A and B. As with layers A and B, layer D showed an increased rate of density increment after considerable melting above it began.

Layers E, F, G, and H all show practically the same relationship and are represented by one curve. These layers all showed a smaller initial rate of density increase than layers A or B, but there was only slight diminution of rate of increase after 40 days from deposition as compared with layers A, B, and D. The upward march of density continued at nearly the same rate through the life of these layers.

The curve-slope differences for the various layers indicate that factors other than those indicated by time alone are partly responsible for the increase in snow density.

The slope differences are also believed to indicate that atmospheric conditions prevailing at the time snow is deposited have an important bearing on each snow-layers density as developed thereafter. The relation of snow texture to density, as mentioned, applies in this connection in at least partial explanation of the curve-slope differences in Figure 12.

Uniformity of layer densities (homogeneity)--Water drainage from the snow began in volume about April 15 and this approximate date represents the beginning of the main melting season. On this date, there was a fairly wide spread of snow-layer densities, ranging from 41 to 55 per cent; by April 28 the spread was from 45 to 58 per cent; by May 13 the spread was less, ranging from 47 to 56 per cent; and by May 26 the spread was only from 50 to 56 per cent, but the layer comparisons were fewer than on any previous date. It appears that, as melting progressed, snow density became a little more uniform. However, examination of layers A, B, and D, all of which existed on April 15 and 28, and May 13 and 26, shows the density spread between these layers on the above dates to be 5, 7, 6, and 6 per cent, respectively. Apparently, in the lower layers,

homogeneous snow had not developed after melting had been under way for six weeks.

Morphology studies of these layers during this six-week period also showed that snow texture and structure were relatively the same after melting had been under way for six weeks, as at the period's beginning. It is concluded that snow does not necessarily become homogeneous after melting begins.

Layer-water equivalent--Prior to March 3, each layer's water content or equivalent was computed by multiplying the layer thickness in inches by lateral density in per cent. Measured thickness of each layer throughout the season is shown in Table 3. Lateral densities of each layer at the original mid-point are shown in Table 2. The lateral horizontal samples in most cases closely reflected the average density of each two-week snow layer at each sampling. This is demonstrated by multiplying the average density of each layer by its depth, or thickness, and comparing the summation of water content thus computed for all layers with the total water content measured in the duplicate vertical holes at each sampling. Beginning March 3 and bi-weekly thereafter, each snow-layer's water content was directly measured by duplicate vertical samples. Beginning then, the computed and measured water content of each layer may be directly compared. These comparisons are included in Table 4.

Table 3--Observed thickness of each snow layer as measured in experiments at Crater Lake, Oregon, 1940-1941

Layer	1940				1941											
	Nov. 14	Nov. 28	Dec. 9	Dec. 23	Jan. 6	Jan. 20	Feb. 3	Feb. 17	Mar. 3	Mar. 17	Mar. 31	Apr. 15	Apr. 28	May 13	May 26	June 2
	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in
A	29.5	26.0	21.6	21.9	22.6	22.0	21.2	20.8	20.4	20.9	19.2	18.8	17.2	16.6	15.8	15.0
B		2.5	1.8	2.2	2.2	1.6	1.5	1.9	2.0	1.8	2.0	2.0	2.2	2.2	2.0	1.8
D				25.0	17.0	16.1	15.5	15.2	15.0	14.0	12.9	12.6	13.7	14.1	13.5	6.0
E					40.7	28.5	24.5	21.1	19.0	18.9	18.5	18.2	16.8	16.2	3.0	0.0
F						42.8	28.8	22.0	20.2	18.0	17.6	17.4	15.2	15.0	0.0	0.0
G							29.0	21.0	18.2	16.0	14.4	14.2	13.2	6.0	0.0	0.0
H								20.5	14.6	11.8	11.1	9.8	3.9	0.0	0.0	0.0
I									12.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
K											a	...	...	...	...	...
L												11.8	0.0	0.0	0.0	0.0

[a] 1 inch included with layer H

It was noted that vertical density of each layer, as shown in Table 5, was usually, although not always, greater than its lateral density. This is clearly shown in Table 6, where each layer's vertical density is expressed as a percentage of its lateral density at each sampling. As B layer was too thin to permit accurate vertical sampling, it was always included with A in the vertical sampling. Therefore, in order to compare A + B vertically with A + B laterally, the observed lateral densities of A and B were weighted as indicated in approximate ratio of their respective water contents to their total and the resultant average was compared with the vertical density of A + B. Both the lateral and vertical sampling tubes and contents were weighted each time with the same snow balance. Both tubes had cutters of the same diameter; therefore, the lateral density must have averaged less than the vertical density in most layers at most samplings for one of two reasons: (1) Layer densities were not uniform and relatively more mass of snow per inch depth was present in certain layers below the original mid-point than above. (2) The number of density observations at each sampling, both lateral and vertical, was so few as to permit large arithmetical deviations from a true value in the expression of their mean.

The fact that vertical density exceeded lateral density in most layers (27 out of 38 cases, see Fig. 6), discredits the second explanation, or at least reduces its applicability, since such consistent differences in so many measurements could not be logically attributed to chance. The reason for the differences, in most cases, at least, lies then in the first explanation. For instance, examination of Figure 9 discloses that after the original sampling of layer F on January 20, the original mid-point settled less rapidly than the surface of the layer. This had the effect of bringing the original mid-point closer to the layer surface, and indicated greater snow density in the lower part of the layer than in the upper part. Consequently, there would be more mass per inch of depth in the lower portion of the layer, and a vertical sample would show greater average

Table 4--Computed and measured water content of each layer of snow as determined in experiments at Crater Lake, Oregon, 1940-1941

Layer	1940				1941											
	Nov. 14	Nov. 28	Dec. 9	Dec. 23	Jan. 6	Jan. 20	Feb. 3	Feb. 17	Mar. 3	Mar. 17	Mar. 31	Apr. 15	Apr. 28	May 13	May 26	June 2
	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in
A[a]	7.0	8.7	9.0	8.6	9.0	9.1	9.0	8.8	8.2	8.5	7.2	8.5	8.4	8.0	8.1	7.5
B[a]		0.6	0.7	0.7	0.8	0.6	0.6	0.7	0.8	0.8	0.9	0.7	1.0	1.0	1.0	0.8
A+B[a]	7.0	9.3	9.7	9.3	9.8	9.7	9.6	9.5	9.3	9.3	8.1	9.2	9.4	9.0	9.1	8.3
A+B[b]	8.1	8.2	9.7						9.2	8.8	9.0	8.5	9.6	8.3	9.2	7.7
D[a]				8.2	6.4	6.9	6.8	6.7	6.6	6.4	6.2	6.1	7.1	7.4	7.6	0.0.
D[b]									7.5	6.9	6.0	6.5	7.1	8.0	8.1	5.0
E[a]					9.3	9.3	9.1	8.8	8.4	9.1	9.7	10.0	9.8	9.0	0.0	0.0
E[b]									7.4	9.8	10.6	10.7	10.0	9.3	2.2	0.0
F[a]							8.3	7.9	7.2	7.6	7.3	8.5	8.6	8.2	8.0	0.0	0.0
F[b]									7.5	8.0	8.8	7.7	9.0	8.3	0.0	0.0
G[a]								6.6	6.0	6.2	6.1	6.4	6.4	6.3	0.0	0.0	0.0
G[b]										6.5	6.4	7.0	6.9	6.8	3.0	0.0	0.0
H[a]									4.1	3.9	4.4	4.8	4.1	0.0	0.0	0.0	0.0
H[b]										4.6	5.2	4.2	5.2	2.4	0.0	0.0	0.0
I[a]										3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
I[b]										2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L[a]													4.8	0.0	0.0	0.0	0.0
L[b]													4.6	0.0	0.0	0.0	0.0
Total[a]	7.0	9.3	9.7	17.5	25.5	34.2	40.0	42.3	44.7	42.6	43.7	48.5	40.8	36.4	18.9	13.3
Total[b]									45.6	45.1	45.6	50.0	43.9	36.9	19.5	12.7
Total[c]	8.2	8.2	9.7	16.2	25.0	34.2	40.1	42.7	45.5	44.3	45.2	47.2	42.6	35.5	17.7	11.2

[a]Computed by multiplying layer thickness by lateral density. [b]Measured by vertical sampling of each layer in plot center. [c]Average total water content by vertical samples of all layers combined along west and east plot edge.

Table 5--Vertical density of each snow layer as determined in experiments at Crater Lake, Oregon, 1940-1941

Layer	1941							
	Mar. 3	Mar. 17	Mar. 31	Apr. 15	Apr. 28	May 13	May 26	June 2
	pct	pct	pct	pct	pct	pct	pct	pct
A+B[b]	42.8	41.3[a]	42.1	45.0	51.2	48.8	53.2	46.1
D	46.2	49.2	52.6	48.3	60.3	56.0	60.0	60.0
E	37.9	50.8	54.3	54.8	56.7	57.6	55.4	. . .
F	37.0	46.0	52.0	55.0	56.8	55.3	. . .	. . .
G	35.6	41.6	48.8	48.7	53.8	58.2	. . .	. . .
H	31.8	40.0	38.8	48.0	49.8	. . .	. . .	. . .
I	23.4	. . .	. . .	. . .	. . .	. . .	. . .	. . .
L	. . .	. . .	. . .	37.9	. . .	. . .	. . .	. . .

[a]Average of three samples. [b]The lateral density of A (Table 2) was weighted with B, 8 to 1 for comparison with the vertical density of A+B.

density than a lateral sample at the original mid-point. In layer G the same conditions existed as in layer F. In layer D the vertical density similarly exceeded the lateral density. In the case of this layer, snow morphology studies showed the upper part of the layer to be granular, whereas the lower portion, beginning about one inch below the lateral sample hole, was very fine and dense in texture. The lower portion of the layer would then be expected to have a greater water content. The comparison of vertical and lateral densities of layer D showed this to be the case. Lateral check measurements in the upper and lower parts of D on May 26 showed the density of the lower part to be about eight per cent greater than that of the upper part.

Table 6--Vertical density of each snow layer as a percentage of each layer's lateral density as determined in experiments at Crater Lake, Oregon, 1940-1941

Layer	1941								
	Mar. 3	Mar. 17	Mar. 31	Apr. 15	Apr. 28	May 13	May 26	June 2	Aver.
	pct	pct	pct	pct	pct	pct	pct	pct	pct
A+B	107	100	110	100	106	101	103	97	103.0
D	106	107	109	100	117	106	107	..	107.4
E	85	105	103	99	97	103	...	..	98.7
F	98	113	108	111	105	104	...	..	106.5
G	105	108	110	108	113	...	...	..	108.8
H	119	106	89	115	...	...	...	..	107.2
I	98	...	...	...	...	...	...	..	97.5
L	...	...	...	93.	...	...	...	..	93.3
Average	102.5	106.5	104.8	103.7	107.6	103.5	105.0	97.2	...

In layer A+B, lateral and vertical densities compared very closely. This was expected from the uniform granular nature of these layers. Similarity of the vertical and lateral densities indicates there was no important capillary water fringe above the ground surface in layer A. Such a fringe was looked for at each bi-weekly examination and was not observed during the experiment.

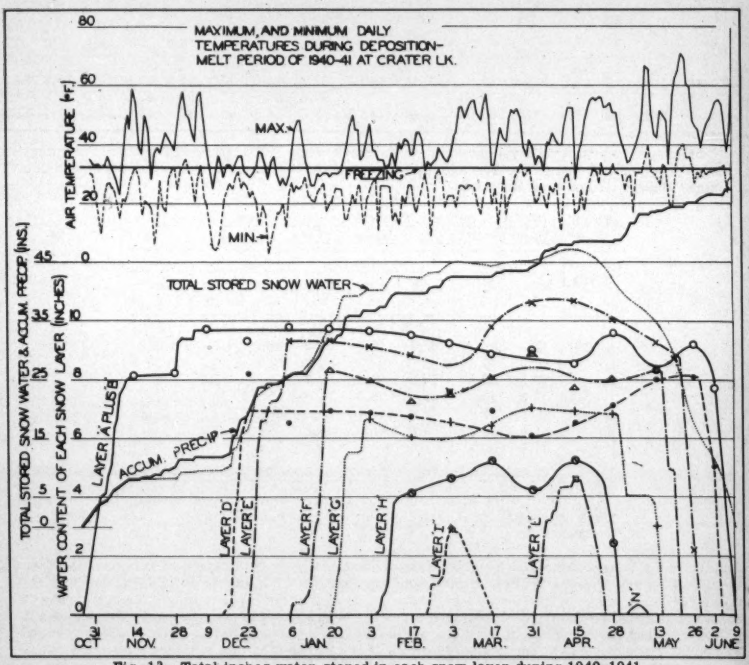

Fig. 13--Total inches water stored in each snow layer during 1940-1941 deposition-melt season at Crater Lake

Water content of each bi-weekly snow layer is plotted in Figure 13. Plotted water contents prior to March 3 are as computed and those for March 3 and thereafter are as measured by vertical layer sampling. The following points with regard to each layer are shown by the curves:

Layer N fell and melted between sampling dates, so its water history is unknown.

Layer M existed insignificantly on April 16 and 17.

Layer L was deposited beginning April 2, reached a total water content estimated at 4.7 inches by April 9. The layer melted rapidly after April 15 and had disappeared by April 26. Nearly all its melt-water passed entirely to the ground; of all layers below, only D showed any water increase (0.3 inch). Therefore, in this period the density of all layers beneath L, except layer D, were at their maximum water-holding capacities.

Layer K was only one inch snow depth on March 31.

Layer J existed only as an insignificant layer on March 5.

Layer I deposited between February 23 and March 3 reached a water content of 2.8 inches. All this water was lost between March 5 and March 18. As melt-water from layer I percolated through the snow, it was held by lower layers H, G, F, and E. Total water increase in these layers was 2.8 inches.

Layer H gained water rapidly early in its deposition period, February 6-12, inclusive; then from February 12 to about March 3 it gained water slowly from precipitation not held in layer I. It gained a little more from the melting of layer I and after the disappearance of layer I on March 18, and with consequent exposure of its surface to the Sun's rays, it melted until covered by layer L beginning April 1. Melting from layer H then immediately stopped and restoration of layer water began again from precipitation not held by layer L. Layer H reached a secondary peak volume water storage about April 15, but after second exposure of its surface by the disappearance of layer L on April 26, it lost water at a rapid rate (about 4.8 inches in five days) and had all melted away by April 30. Of the 4.8 inches of water released, only 0.3 inch was retained below (in layer D); so approximately 4.5 inches of water from layer H either evaporated or passed downward to the soil beneath. Limited evaporation data available indicate that practically all this water went into the soil.

Layer G gained water rapidly between January 21 and 26 and a lesser amount on February 1. It appears to have retained a fairly uniform water content from February 1 until its surface became exposed by the complete disappearance of layer H on April 30. Beginning then, layer G lost water rapidly until its disappearance on May 15. The total loss of layer G between April 30 and May 15 was 6.8 inches, but the shape of the loss curve is not definitely known because of the masking effect of layer N. Nearly all of the water from layer G passed through lower layers to the soil beneath.

Layer F gained most of its water in the heavy storms of January 12-19 and appears to have lost about one inch water from January 20 to February 17. However, since the water-content values for this period plotted on Figure 13 are computed, it might be held that the appearance of water loss may not represent the true condition, but rather results from using lateral density values that may have been greater than the vertical density, thus resulting in a computed water content greater than that actually present. This assumption is believed incorrect, however, as on every sampling but one in layer F after March 3, the lateral-density figure undervalued the water content. No reason is apparent why this difference should not be carried back into the early history of the layer, and if this were done, total water contents on January 20, February 3, and 17, would be even greater than those plotted in Figure 13. It appears, therefore, that layer F lost at least one inch of water between January 20 and February 17. Layers immediately above and below layer F showed similar loss during the period. Beginning about March 3, layer F began to increase slowly in water content, presumably holding part of the melt-water reaching it from the melting of layer I, and from March 17-31 this layer further increased in water content by 0.4 inch. Layer E, immediately below, increased 0.8 inch in water content and layer G immediately above layer F increased 0.6 inch in water content in the same period. Total increase in these three layers was thus 1.8 inches. This increase was more than accounted for by 1.7 inches precipitation in the period, March 18-31, inclusive, plus 0.6 inch melt-water passing down from layer H. Between March 31 and April 28, layer F apparently lost a little water for reasons not clear, and from April 28 until its surface became exposed by the disappearance of layer G on May 15, layer F gained water slowly, doubtless from melting of layers N, G, and H above. From

May 15, the day layer F became exposed to the elements, it lost water at a very rapid rate (8.0 inches in six days) and the layer ceased to exist on about May 22.

Layer E, deposited between December 23 and January 6, appears to have lost a little water from time of its first measurement until about March 3. As its water content prior to March 3 is computed from lateral samples, this indication is not too certain, since the differences in its water content so determined were very small on January 6 and 20, and February 3 and 17. From about March 3 until about April 7 it gained materially in water content, holding some of the water which percolated down from melting layer I and from the precipitation of March 18-31 inclusive. After about April 7, this layer lost water slowly until its surface was uncovered by the disappearance of layer F on May 22. The E layer then lost water at a fast rate (8.8 inches water in seven days) until its disappearance on May 28. A change in E layer snow texture appears responsible for its slow loss of water from April 7 to May 15. The morphology studies indicated that this layer became much coarser in texture between April 15 and 28. Its lateral density increased only slightly in the same period, and not so much proportionately as its thickness decreased; its lateral density decreased between April 28 and May 13, showing a water loss.

Layer D, mostly deposited between December 14 and 23, retained practically a uniform water content until about March 28, but from then until the layer's exposure by the disappearance of layer E on May 28, it gained about two inches in water content. This increase seems defined by several measurements and appears to be due to water feeding down to the layer from melting of layers L, H, N, G, F, and E. At least one possible reason for D retaining this melt-water from above lies in the heavy ice layer (numeral 2 in Figure 14) on the surface of snow layer B. It seems that this ice layer prevented fully free percolation of water through layer B, and a capillary fringe in layer D above the ice layer may have resulted, although such a fringe was not observed. After the exposure of layer D on May 28, the layer melted very rapidly (8.0 inches water in six days) and completely disappeared by June 3.

Layer B was so thin that it could not be sampled vertically with accuracy, therefore it was included in this particular study with layer A.

In layer A+B, layer A accounts for most of the water. Layer A was built up steadily from October 28 to November 14 and its water content was 8.1 inches on November 14. The B part of the layer was deposited between November 16 and 25 and its water content amounted to less than an inch. However, rains between November 28 and December 9 brought the water content of the combined layers up to about 8.7 inches, where it remained for several weeks. The A + B

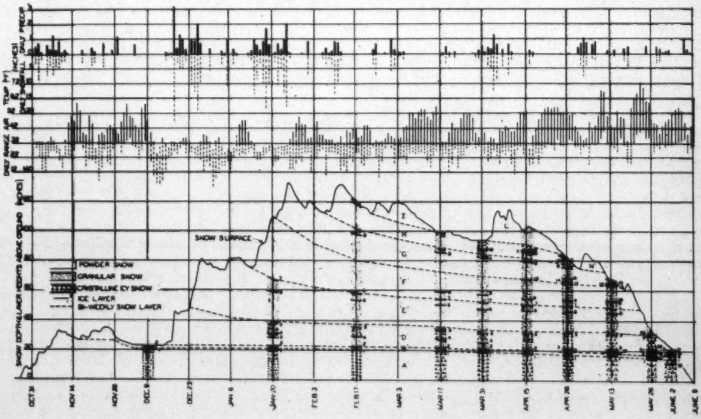

Figure 14--Snow morphology and weather at Crater Lake, 1940-1941

layer appears to have lost a little water between about February 1 and April 15, owing, it is presumed, to increased granulation of the layer with time. Between April 15 and 28 it increased in water content which was judged to be due principally to a very wet soil surface as observed on April 28 and to the ice layer which formed on the ground between April 15 and 28. That ice layer was porous, but in conjunction with the saturated soil, doubtless offered just enough obstruction to water percolating through layer A to create a capillary fringe above the ice layer, resulting in increased water content. This fringe was not observed.

Water content of A + B decreased 1.5 inches between April 28 and May 13 owing to drainage from A + B exceeding the melt supply from above, which in turn was decreased by cold, stormy weather. The ice layer on the ground had partly disintegrated by May 13 and did not cover the ground surface uniformly.

Between May 13 and 26, water content of A + B increased 0.9 inches, owing again, it is believed, to a greater downward percolation of melt-water from layers F and E than would readily pass through the ice layer on the ground. The ground surface was observed on May 26 to be very wet. The water content of the A + B layer again diminished 1.5 inches from May 26 to June 2, owing to decreased percolation rate of melt-water from layers above. After the surface of A + B was exposed by the melting of D, the layer lost water very rapidly (7.7 inches in seven days) and on June 9 the ground surface again became directly exposed to the Sun's rays after having been covered by snow continuously for 225 days.

Relation of density to snow depth--The writer for several years thought that snow of great depth tended to show higher density in the column's lower portion than snow of shallow depth. This belief, based on casual observations during routine snow surveying, seemed logical, as snow of great depth possesses weight, and melt water passing downward has a greater span of time in which to change the lower snow density than is possible with shallow snow.

When digging through 84 inches of snow to secure soil samples on Annie Spring snow course in Crater Lake National Park, lateral snow samples were secured from a pit on March 20, 1940. Thirteen horizontal samples spaced six inches apart in a vertical line were taken with a Federal snow sampler driven 60 inches for each sample. To insure complete cores, a second pit was dug paralleling the first and separated from it by a snow wall 60 inches thick. A mitten held against the second pit's wall prevented snow from breaking out ahead of the sampling-tube point as it penetrated from the initial pit. Complete snow cores thus secured were weighed separately and water content of each was determined. Average core density of each hole was computed by dividing the water content (inches) by length of sampler drive (inches).

Results in Table 7 show marked density differences throughout the column. Melting had not begun, as far as could be observed, when these samples were taken. Snow density at or near the surface was essentially the same as snow density within a few inches of the bottom of the snow pack.

Table 7--Snow density at differing depths from snow surface to earth beneath at Station 0+04, Annie Spring, Oregon snow course, March 20, 1940

Sample No.	Depth	Snow density	Remarks
	in	pct	
	0	. . .	Snow surface
1	6	44.0	
2	12	44.6	
3	18	38.4	
4	24	38.8	
5	30	41.6	
6	36	42.5	
7	42	44.5	
8	48	44.8	
9	54	44.8	
10	60	47.8	
11	66	47.3	
12	72	45.2	
13	78	45.3	
	84		Ground surface

Additional data bearing on this point are shown in Figure 15, in which lateral density of each layer of the 1941 experiment is plotted against weight of the snow overburden (inches of water) above the original mid-point of each layer. In preparing data for plotting, it was assumed that half of the weight of each layer was above the mid-point. This assumption was not strictly correct, but the difference between the actual and assumed condition had no practical effect on the result. The weight of all superimposed layers was determined by water content of each layer as measured after March 3, or as computed before that date.

For purposes of simplifying curve comparisons, Figure 16, showing the pattern curves of Figure 15, but without plotted points, was prepared. This figure could be conceived as three-dimensional with time as depth. There appeared no relationship between weight of overlying snow and density of lower layers;

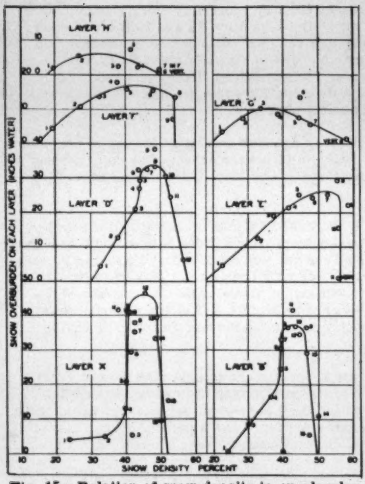

Fig. 15--Relation of snow density to overburden and time in consecutive snow layer samplings, Crater Lake, 1940-1941

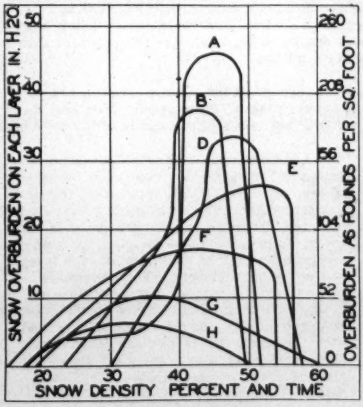

Fig. 16--Curve-pattern relation of density to overburden and time

is shown.

or at least, if such a relationship exists, as suggested by DEFANT [1908], it was obscured in this experiment by other factors. In fact, Figure 16 seems to show that the less the weight of snow overburden, the greater the density increase per unit of overburden. Furthermore, the curves for every layer are of such shape as to show that time (of which melting is an accompaniment) is the dominant factor in build-up of snow density. It therefore appears that overlying snow burden has little if any effect upon density of underlying snow.

CHURCH [1940] found regular settling of ice layers regardless of amount of snow overburden.

Snow melting--It is shown from the studies of layer-water equivalents that practically all snow melting, that is, actual water loss, was from the snow surface and not from the snow-earth plane. This showing differs from ALPS' [1922] conclusions that "snow disappears simultaneously from the top and the bottom." CHURCH [1940] suggested that snow may melt from below. CLYDE [1931] also said that melting occurs both at the top and bottom, but he inclined to the opinion that most important melting was from the snow surface. Figures 17 and 18 visually demonstrate the snow-surface melting near the experimental plot.

CLYDE [1931] found that one day degree Fahrenheit of temperature melted 0.091 inch depth of water as snow. This was the average for 16 days in late April and early May. HORTON [1915] found that one-day degree Fahrenheit of temperature above freezing melted from 0.04 to 0.06 inch depth of water. In the Crater Lake experiments, melt values for one day-degree Fahrenheit temperature above 32° were found as shown in Table 8. The values found more closely approximated those for Utah than for the eastern United States, but show that a rather wide range exists in melt values during the season. It appears that melt values are not constant per day-degree of temperature above 32°. Day-degree constants are therefore not considered dependable for estimating amount of melt that might be produced from any given volume of snow. Hour-degrees above 32° would be more dependable, but factors other than hour-degrees alone may profoundly affect rate of snow melt.

Snow morphology--Observations of the size and arrangement of ice crystals in the various layers were made at irregular intervals through the experimental period, as shown in Figure 16. Observed height of all ice layers above ground

The principal items of interest here are as follows:

(1) Ice layers formed when the snow surface was directly exposed to the elements retained

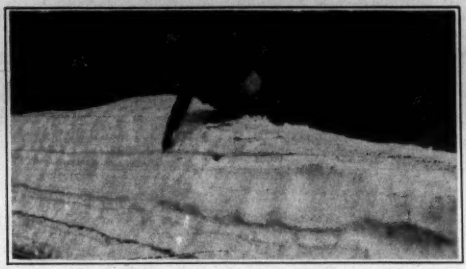

Fig. 17--Showing ice layers in road-side snow three miles west of experimental plot on May 13, 1941; layer pointed out is believed to be No. 8 shown in Figure 14

Fig. 18--Pointing out layer 8 at same location as in Figure 17 above, but two weeks later; note how snow above layer 8 has disappeared since May 13, but lower snow layers are relatively unchanged

their identity through the weeks until melted by direct surface exposure. Illustrations are ice layers 1, 2, 5, 6, 7, and 8, which were all formed at the snow surface, either during clear weather with daily freezing and thawing, or during cloudy weather when rain fell on the snow surface and this surface subsequently froze.

(2) Other ice layers apparently were formed at the snow surface, but were so similar in character to surrounding snow that they escaped observation until later in the season when the surrounding snow had changed in structure or texture in such fashion as to define the ice layer. Layers 3, 13, and 15 are believed to illustrate this type of ice layer.

(3) Other layers were formed by freezing in the snow body of downward percolating melt-water. Downward percolation from the snow surface ceased when air temperatures dropped below freezing, and if freezing temperatures were sufficiently low and of long enough duration, the melt-water was refrozen at its level of maximum penetration in the snow body. Layers 10, 11, 12, 14, 17, 18, 19, 20, 21, 22, and 23 are believed to be of this type. HORTON [1915] mentions ice layers formed in this fashion.

Apparently none of the ice layers observed at Crater Lake were impervious, and water seemed to pass freely through them all, except layers 1, and 2, which did not always pass water through as rapidly as it reached them from above.

Under weather conditions such as prevailed at Crater Lake in 1940-1941, the snow, by alternately freezing and thawing, gradually acquired an icy granular texture and the individual ice crystals tend to assume a rounded form.

Ground freezing--The soil was unfrozen on each date of snow-density observation until December 23, when the ground was observed frozen to a depth of 2.5 inches. To check this observation, another test was taken about 25 ft south of the plot and the earth there was found frozen to a similar depth. On January 6 the soil was frozen to a depth of 0.5 inch and on January 20 it was frozen only to a depth of 0.1 inch. After and including February 3, the ground was observed to be unfrozen.

It appears that the cold snap of December 12-16 inclusive, when the daily minimum air temperature ranged from +22° F to +4° F and daily maximum went only once above 32° F, encouraged frost penetration through the 24-inch snow cover into the ground beneath. This icy, granular snow had a density of about 42 per cent.

The frost slowly left the ground as air temperatures moderated and snow depth increased. The ground thawed from below toward its surface, rather than downward from the surface. Soil temperature readings are shown in Table 9.

Table 8--Melt values determined in experiments at Crater Lake, Oregon, 1940-1941

Date	Snow-stored water	Loss of water	Day-degrees F above 32°	Melt loss per day-degree F above 32°[a]
	in	in		in
Mar. 3	45.50			
Mar. 17	44.30	1.20	44.4	0.027
Apr. 15	47.20			
Apr. 26	42.60	4.60	56.8	0.081
Apr. 28	42.60			
May 13	35.45	7.15	58.3	0.123
May 13	35.45			
May 19	30.15	5.30	14.3	0.370
May 19	30.15			
May 26	17.70	12.45	88.6	0.140
May 26	17.70			
June 2	11.25	6.45	9.8	0.658
June 2	11.25			
June 9	0.0	11.25	43.2	0.260
Total and average		48.4	315.4	0.153[b]

[a]Includes evaporation. [b]Value obtained by dividing total water loss by total day-degrees F above 32°.

Table 9--Temperature in each snow layer beginning February 17, as recorded in experiments at Crater Lake, Oregon, 1940-1941

Layer	1941								
	Feb. 17	Mar. 3	Mar. 17	Mar. 31	Apr. 15	Apr. 28	May 13	May 26	June 2
	°F	°F	°F	°F	°F	°F	°F	°F	°F
Soil[a]	32.2	...	32.2[b]	33.6	32.6	32.4	32.0	32.0[c]	32.3
A	31.6	31.7	31.8	31.8	31.8	31.8	32.0	32.0	32.0
B	31.2	31.6	31.8	31.8	31.9	31.8	32.0	32.0	32.0
D	31.1	31.6	31.8	31.8	31.8	31.8	32.0	32.0	...
E	30.4	31.7	31.8	31.8	31.8	31.8	32.0	...	...
F	29.4	31.6	31.8	31.8	31.8	31.9	32.0	...	...
G	28.4	31.6	31.9	31.9	31.9	31.9	...	...	...
H	27.2	31.6	31.9	31.9	32.0	...	...	...	...
I	...	31.6	...	...	...	...	...	...	...
L	...	...	...	...	31.9	...	...	...	...

[a]Reading taken 1 1/2 inches below ground surface.
[b]Temperature six inches below ground surface 33.0°; 10 inches below 33.5°
[c]Temperature was 33.0° under space on ground ten inches × four inches not covered by ice.

Ice on ground--It is common knowledge among snow surveyors that a layer of ice often forms on the surface of unfrozen ground after snow-melt begins in the spring, but this is not always true. HORTON [1915] offered the following explanation of this phenomenon: "With thawing days

Table 10--Conditions favoring build-up of ice on ground, as noted in experiments at Crater Lake, Oregon, 1940-1941

Date	Snow depth	Range of temperature in snow	Soil temperature 1 1/2 inches below surface	Thickness of ice on ground	Remarks
1941	in	°F	°F	in	
April 15	103.0	31.7-32.0	32.6	None	Discharge of water from snow beginning; soil unfrozen and moist.
April 28	83.0	31.8-32.0	32.3	0.25	Discharge of water from snow under way; soil unfrozen and wet.
May 13	68.0	31.9-32.0	32.0	0.37-0.50	Some parts of ground surface not covered by ice; discharge continuing; soil unfrozen and very wet.
May 26	32.0	32.0	32.0	0.37-0.50	Some parts of ground surface not covered by ice; discharge continuing; soil unfrozen and very wet.
June 2	22.5	32.0	32.3	0.31-0.44	Not as great a portion of the soil surface covered by ice as at previous observations; ground surface less wet than any date after April 15.

and freezing nights, most of the water resulting from the melting of snow lying upon impervious ground will percolate to the bottom of the layer and may there be held by capillary action until subsequent cold converts it into a layer of ice. It may remain as ice until most of the snow above it is melted. This explains the layer of ice commonly observed around the margin of a snow bank as it melts..."

ALPS and HAMMONDS [1920] noticed a one-quarter inch thick ice layer on wet but unfrozen ground at Summit, California, on May 13, 1920.

Horton suggested the phenomenon was found on "impervious" ground, but it was observed in 1941 at Crater Lake where the soil is very pervious. Build-up of ice on the ground here occurred under conditions shown in Table 10.

It appears that percolating snow-melt water at a temperature of 32° reduced the surface-soil temperature to 32° after melting began. A very shallow capillary fringe must have been created in the snow above the ground surface, although no such condition was observed. Minimum daily air temperatures ranging down to 18° F and below freezing on nine days between April 15 and 28, apparently penetrated the snow to the capillary fringe and formed the ice layer there. This ice layer was porous at all times and water passed through it freely. Horton's explanation could apply to the phenomenon observed at Crater Lake.

Miscellaneous observations--On May 26 it was noted that grass was growing in the soil beneath the snow. The shoots were approximately one inch in length and were tipped with green. Snow depth was then 32.0 inches. Light is required for photosynthesis, so it follows that light was penetrating the snow cover prior to its recession in depth to 32.0 inches. A week earlier the snow cover was 63.2 inches deep at the plot.

Summary and conclusions

(1) The customary April 1 final spring snow survey date, for all practical purposes, measured the peak accumulation of snow-stored water at Crater Lake in 1941 and was almost an exact measure of total precipitation there from the time snow first remained on the ground in late October of 1940.

(2) Rain falling on shallow snow of relatively low density may pass through to the ground beneath and contribute but little in transit to the snow-stored water.

(3) Rain falling on moderately deep snow of low or intermediate density may be retained in the snow.

(4) Snow density cannot accurately be estimated from measurements of snow depth alone, any more than density of one portion of the snow cover can be computed from known density of another portion of the total layer.

(5) Snow settling is a continuous process from the time snow first remains on the ground. Diminishing snow depth early in the winter is due more to settling and less to melting at the surface, but diminishing snow level later in the season is due nearly altogether to melting away of the surface snow, rather than to snow settling.

(6) Density of snow generally increases consistently from the time snow is deposited until it disappears.

(7) Density of new-fallen snow increases more rapidly in any given time period than density of older snow.

(8) There is no single relationship between elapsed time after deposition and mature snow density.

(9) When important melting began, the water did not leave the snow at a constant rate, but rather at a rate generally accelerated with time and decreasing snow depth. A general upward air temperature trend accompanied it.

(10) Short periods of density decrease, after melting begins, may be due to continued water drainage from the snow without replenishment from surface melting.

(11) Density is directly related to the size and arrangement of the ice crystals comprising snow. In general, snow of fine texture having rounded crystals, and lubricated by melt-water from above, will have a higher density than snow of equal or older age but having coarser texture or very open structure.

(12) Snow does not necessarily become homogeneous in texture after melting begins. Its density may similarly lack homogeneity.

(13) Ultimate density of any long-lived, deeply buried snow layer may be partly dependent upon the atmospheric conditions under which the snow crystals are first formed. Ultimate density of any particular snow layer may, accordingly, be partly determined before its flakes reach the ground.

(14) There appears to be no relationship between weight of overlying snow and density of lower layers.

(15) In this series of observations, it was definitely determined that practically all snow melting occurred at the snow surface and only insignificant melting occurred at the snow-earth plane.

(16) Water melting from snow (and including surface evaporation) at elevation 6540 ft, averaged 0.153 inch per day-degree Fahrenheit temperature above freezing at Crater Lake in 1941.

(17) Melt values are not constant per day-degree of temperature above 32°F.

(18) The maximum water-holding capacity of any snow layer of given depth is not constant, but varies with structure and texture of the snow. In general, its maximum water-holding capacity increases with age.

(19) The density and water content of any snow layer after melting begins may be increased by the presence of an ice layer immediately below or within the layer.

(20) Two common types of ice layers are those found at the snow surface and later buried within the snow body by new-fallen snow, and those formed within the snow body through freezing fixation of percolating melt-water. A secondary form of the first type is the ice layer which excapes observation until the surrounding snow changes its texture.

(21) Frost will penetrate a snow cover at least 24 inches thick to freeze the earth beneath.

(22) Frozen soil beneath the snow may thaw from upward conduction of heat stored in the deeper ground and not necessarily from direct radiant heat conducted through the snow.

(23) Light sufficient to form chlorophyll in newly sprouted grass penetrated at least 35 to 40 inches of dense snow.

Acknowledgments--At the time these experiments were performed, W. T. Frost, Park Ranger, National Park Service, United States Department of Interior, furnished valuable assistance in the experiments, as did also R. W. Childreth, formerly, Agent, United States Soil Conservation Service. The author expresses his appreciation to G. F. Sturdevant, Snow Surveyor, Soil Conservation Service, and to O. W. Foiles, United States Park Ranger, for assistance in field work. The United States Weather Bureau furnished certain meteorological instruments.

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DISCUSSION

Forrest L. Rhodes (Cooperative Snow Investigations, Corps of Engineers, San Francisco, California)--This paper clearly brings out the many factors influencing the changes in the density of layers within the snow pack. The thought that depletion of free water within the snow does not occur suddenly but results from hydrological withdrawal from storage (within the snow) at rates greater than recharge is definitely stated. This paper, as a result of investigations made in 1941, further substantiates the need for additional programs to study the hydrodynamic phenomena and the physics of snow melt in conjunction with one another.

Possibly a reason for the selection of such a site for the studies made in connection with the preparation of this paper would have helped in reviewing the results of the investigations. For instance, was the location selected considered to be typical in exposure, vegetal cover, geology, and meteorology of the basin as a whole and to which the results could be applied? Apparently, the pervious pumice soil was selected purposely to avoid melt-water backing up into the snow. It would have been interesting to have studied or noted whether or not the snow on the slopes of different exposures, reasonably adjacent to the sample plot, went through the same changes in the course of melting.

I would like to raise a number of minor questions which do not require detailed discussion but may help in analyzing the results:

(1) Because of the discrepancy between the snow survey and precipitation-gage values, would the use of two gages have been better? Also, was the gage shielded or unshielded?

(2) Why was the anemometer located at 18 inches instead of some other height above the snow?

(3) Were there regular observations of crystal structures and what was the basis of classification for distinguishing the variation? Did the back-filling of the snow have sufficient effect on the original crystal structure to have affected the transmission characteristics of the pack?

(4) In a number of instances "water content" or "snow-stored water" was used. Were these terms identical and also the same as water equivalent?

(5) How were day-degree values computed on an hourly basis? Did this study warrant any compensation for below-freezing temperatures and to ascertain whether the day-degree factor varied as a function of humidity or wind?

I am reluctant to discuss the paper in too much detail as this is only a partial summary of the work conducted. However, some of the results indicated are very good and procedures resulted in the development of a unique lateral snow sampler. The care and the effort in procedure have been clearly brought to attention. However, it will be interesting to know if additional studies have been carried on in this area and, if so, have the results of this paper been substantiated?

Most of the conclusions have been carefully drawn. However, the question of sufficient proof to support some of these conclusions is raised. For example, although soil temperatures were reported to be as high as 33.6°F, 1 1/2 inches below the surface, yet it was determined that the melting of snow from underlying soil was insignificant. I do not believe the results of this paper warrant drawing this conclusion. It is not clear whether some of the statements made in this paper are a product of the observations made in this experiment. A number of the conclusions, it seems to me, would be influenced by the water-holding capacity of the snow pack. Careful thought should be given to terms such as; "percolation rate" being distinguished from "melting rate," "maximum water-holding capacity" as studied with retention and detention factors of various types of snow. What observations were made of water-holding capacity? The use of standard thermometers for measuring snow temperatures is quite questionable due to the ability of the glass tube to readily absorb direct radiation giving results which may be higher than true. Apparently, the depth-time-density relationship presents some difficulty to the author in analyzing the data because it is believed that conclusions (3) and (4) are contradictory.

The above paragraph is intended to be a critique to emphasize the need for very careful usage of physical terms in drawing conclusions and is not to detract from the valuable points brought out in the paper. The observation of the green grass beneath 32 inches of snow clearly brings out the personal interest and care used in the actual work.

It is realized that the study of snow and what happens to it and the reasons for it happening are very essential in the final determination of factors influencing stream flow and runoff. This paper shows the details and the conclusions drawn from one phase of snow conditions. Only those persons who are fully cognizant of the problems in connection with the study of snow could have so ably carried out this project. Therefore, we must give credit to those showing such initiative and close interest in these experiments. In final conclusion, we must realize that additional investigations of this type, to further expand our knowledge of the hydrodynamics and thermodynamics of snow through a program of scientific research, are needed.

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THE INFLUENCE OF FOREST COVER ON SNOW-MELT

H. G. Wilm

Abstract--There is presented a survey of important literature on the effect of forest cover on snow-melt, with recent results of investigations in the Fraser Experimental Forest, near Fraser, Colorado. It is shown that forest management by selective cutting influences greatly the accumulation and retention of snow on the ground. The evidence supports J. E. Church's fir forest possessing a maximum number of glades as the most desirable type for snow conservation.

Introduction--In the western United States, as in other parts of the world, water-producing land is commonly covered with forest vegetation; and a very large part of the water yielded by such land comes either directly or indirectly from melting snow. These two facts have naturally led to widespread speculation on how forests affect water yields from snow. Because speculation generally leads to experiment as well as to argument, a fairly large supply of research findings and related reading has been built up in technical literature.

The purpose of this paper is to bring together portions of the literature on how forests affect the accumulation and melting of snow; to summarize the findings of earlier studies, and to add the results of recent experiments; and, finally, to indicate where we seem to stand now in our knowledge of this subject.

Early investigations

Following the development of discussions on forest influences in general, the influence of forest cover on snow began to exhibit some organized thinking around the beginning of this century. Among the first professional men to be stimulated to concrete action was CARPENTER [1901] of Colorado, who made informal studies in the headwaters of the Poudre River shortly before 1900. As shown by some excellent photographs, Carpenter quite consistently found more snow stored under the protection of forest cover than in nearby open areas.

As is generally true of "undesigned" studies, however, the reader necessarily wonders whether these observations exhibited a true cause-effect relation. Because the photographs were taken at or near the edge of open areas, for example, perhaps the drifts exhibited merely a local snow-fence effect which may have disappeared a little farther inside the forest.

The questions of forest influences moved into high gear when CHITTENDEN [1909] published his classic report. This essay presented views on the influence of forests on snow storage which, along with subsequent discussions, were stated with such certainty that they are worth quoting even today:

> The period of snow-melting begins in the open country much earlier than in the forests. At first the melting is due mainly to the direct action of the Sun's rays before there is sufficient warmth in the general atmosphere to produce any effect. The thinly covered areas melt off first and the streams experience a diurnal rise and fall following the warmth of day and the frost of night. Nothing like a flood ever arises from such melting...
>
> Under forest cover this action is interfered with more or less, depending upon the density of the shade. Even after the ground in the open is entirely bare, except under the drifts, the forest areas may still be covered with an unbroken layer of snow...
>
> The forest shade thus holds the snow, which gradually becomes saturated from its own melting, until the heat and warm rains of late spring or early summer arrive, the soft air everywhere pervading the forest depths and finding a maximum exposure of surface to the melting influences... The result is that when the final melting begins, the whole body of snow disappears very rapidly, rushing from every direction into the streams, swelling them to their limit and often causing disastrous freshets. The active melting lasts but a short time, and there is a little opportunity for the water to soak into the ground...

On the other hand, in the open country, the drifts last for weeks after the snow has entirely disappeared from the forest, and continue to yield a supply of water far into the summer. The period of active melting in the open may have lasted four months, that in the forest scarcely as many weeks.

The effect of forests upon the runoff resulting from snow-melting is to concentrate it into brief periods and thereby increase the severity of freshets. This results (a) from the prevention of the formation of drifts, and (b) from the prevention of snow-melting by sun action in the spring, and the retention of the snow blanket until the arrival of hot weather.

Almost two dozen men submitted written discussions of Chittenden's paper, and they showed widely divergent viewpoints and experience. On our particular subject a few selected quotations will show some of the differences in opinion. F. Collingwood, for example, agreed with Chittenden:

The next point controverted by the author is that forests regulate the flow by retaining snow, which slowly melts at a later period, and thus replenishes the streams. In reply to this: the writer well remembers that, in the woods on the hills near Elmira, New York, the drifts remained unmelted long after every bit of snow had disappeared from the cultivated portions of the valley. It was a common remark that there was enough left to add perceptibly to the flood usually expected in June.

George Otis Smith spoke quite strongly for the opposition:

The author's view, that delayed melting of snow is not beneficial, must . . . be challenged. While the writer too has found dry ground beneath a dwindling snow bank, on digging into the sand he has discovered the water beneath. Again, it seems probable that the bottom, as well as the top, of the snow cover is also a melting surface both in the open and in the forest. This is shown by the manner in which certain spring flowering plants penetrate the snow wherever the cover becomes thin. Thus it appears reasonable to believe that the time of snow-melting is a period of contribution to the underground flow, and the total contribution from snow is necessarily largest where conditions favor the longest period of melting . . .

On the subject of the influence of forests on snow-melting, observations will differ somewhat. As contrasted with Chittenden's excellent and detailed observations in the Yellowstone Park, the writer might mention the fact that even later in the same season, July 1, 1899, on Table Mountain, in central Washington, there was snow in the forest at an elevation of 6000 ft; while, at the same elevation in the open, the snow had long disappeared, and the flood conditions on the Yakima River had passed.

Similar viewpoints were expressed by other discussions, as illustrated by a few more excerpts:

It is undoubtedly true that forests reduce the formation of drifts, but the writer's observations and inquiries convince him that the snow in forests does drift to some extent, though much less than in the open, and that it lasts longer into the spring than even the drifts outside . . . in forests the ground is warmer than it is in the open, and indeed that it frequently may not freeze at all under the snow. As the snow melts, it melts at the bottom, and the ground is more ready to absorb it than is the frozen ground in the open. (George F. Swain)

Plates XLIV and XLV show the snow fields of the upper levels of the Owens River drainage on the east side of the Southern Sierras. Particular attention is drawn to the fact that all snow has melted from under the trees or around them and only remains in the drifts in the bare areas between the clumps of trees. (W. H. Leffingwell and A. M. Strong)

Thus the writer's conclusion, based upon experience of snow conditions ranging from the mountains of North Carolina to the glaciers of Mount Rainier, is that the forest does exert a beneficial influence in retarding the melting and runoff of snows, even though, as happens in certain areas, the snowfall is so great as to produce floods in spite of the forest's influence. (Bailey Willis)

You will notice that all of these writers necessarily depended on observation and personal experience, supplemented by a liberal amount of interpretation. As is often the case, the pattern of facts lying behind these observations may have been somewhat obscured by personal viewpoints and other complicating factors.

The Wagon Wheel Gap Experiment--Perhaps the first thoroughly organized field investigation of forest influences on watershed conditions in the western United States was the one at Wagon Wheel Gap, Colorado [BATES and HENRY, 1928]. In the headwaters of the Rio Grande, two small watersheds were placed under experimental control by means of stream-gaging stations, rain and snow gages, snow courses, and other research equipment. After an eight-year calibration period, one watershed ("B") was "denuded" by the removal of all woody vegetation. Over the following seven years, both total water yields and yields during the snow-melt period were substantially increased; the latter by about 22 per cent. The beginning of the spring stream rise was advanced about 12 days by denudation, while the date of the peak "flood" discharge was advanced only three days. Even summer and autumn discharges were somewhat increased. From these facts several conclusions seem evident: Removal of the forest vegetation caused an increase in the amount of water yielded to the stream from both snow and rain; melting started a little earlier, but not enough to exert any important influence on the timing of flood peaks or the availability of water during the irrigation season; and the increases in spring discharges were probably due to decreased interception and evaporation rather than to any reduction in soil porosity, as the augmented late-summer discharges would indicate an ample volume of water in ground-water storage.

Other investigations--Before and during the Wagon Wheel Gap experiments, CHURCH [1908] was making observations of the relation of forests to snow as a part of his research at Mount Rose, Nevada. He concluded that forest cover is desirable, and made two specific points which express its influences so clearly that they have become classics. First, he observed that high-altitude timber, especially near timberline acted to break wind velocities and thereby cause the accumulation of deep snow-drifts; and that these drifts remained "after the canyons' depths have released their snow." His second statement [CHURCH, 1914] should be quoted directly:

> The ideal forest from the viewpoint of conservation is the one that can conserve the maximum amount of snow until the close of the season of melting. Such a forest should not be dense enough to prevent the snow from reaching the ground, and yet should be sufficiently dense to afford ample shelter from sun and wind. The fir forest possessing a maximum number of glades or a forest of mountain hemlock meets these requirements both theoretically and practically.

Interest in these problems continued to be sustained during the successive decades of this century, as indicated by several technical papers that appeared at various times. JAENICKE and FOERSTER [1915], for example, discussed experiments conducted in virgin ponderosa pine at Fort Valley, Arizona, in 1910 to 1913; and a few years later GRIFFIN [1918] published the results of similar studies in the Cascade Range of Oregon and Washington. In both cases forest conditions were compared with nearby open areas; and both sets of studies produced comparable results. More snow was found to accumulate in open areas than under a forest, but melting rates were much higher. In Arizona, "heavy drifts of snow persist throughout the adjacent forest for two weeks or more after the total disappearance of the park snow." And in the Cascades, snow remained an average of 17 days longer in the forest than in open areas; when the latter were bare, an average of 7 1/2 inches of water remained in snow stored in the forest, about 30 per cent of the maximum snow blanket. Almost 20 years later MEAGHER [1938] made very similar observations in the Wind River Experimental Forest in southern Washington, probably not far from the site of Griffin's work.

Working in ponderosa pine in Idaho, CONNAUGHTON [1935] enlarged on earlier studies by including sagebrush land and young second-growth pine as well as open areas and virgin pine forest. Taking the open areas as 100 per cent, the other cover types contained the following comparative quantities of snow at the time of maximum accumulation: Sagebrush 100.9 per cent; pine reproduction, 94.6 per cent; virgin pine lacking an understory of reproduction, 75.5 per cent; and virgin pine with reproduction, 70.2 per cent. The last snow disappeared on about the same date on open and sagebrush areas; about 3 1/2 days later in the virgin forest without reproduction; and about eight days later in the reproduction stand and virgin forest with reproduction.

Exept for the sagebrush included in the last study, all of these western investigations compared only coniferous forest types with open land. To show how a hardwood forest affects snow accumulation and melting, it may be worth while to bring in the results of an eastern study made by MAULE [1934] in the early 1930's. He took samples in a stand of mixed hardwoods (largely oaks) and in open areas, as well as under white pine, red pine, Norway spruce, and eastern hemlock. The largest accumulations of snow were found on open land, and somewhat smaller amounts under the leafless hardwood stand. Below these in sequence were hemlock, white pine, and red pine, while Norway spruce stored the smallest amounts.

Maule made an interesting observation on melting rates. Where protected by adjoining conifer stands, snow remained in the open and under hardwoods considerably longer than under white pine stands. Therefore it was suggested that the best method of planting trees for long-period snow retention might be provided by alternate rows of conifers and hardwoods. Western people will, of course, immediately visualize mountainsides covered with alternating patches of aspen and pine or spruce.

In an attempt at recapitulating knowledge built up by the end of the 1930's, FORSLING [1941] set up the following theses:

> To sum up the effect of forests: Under dense coniferous forests snow accumulation is least, soil freezing is moderate, and snow melt is slowest; under hardwoods and open coniferous forest snow is deepest, soil freezing is prevented or reduced to a minimum, and the rate of snow melt is moderate; in cleared areas snow depths are intermediate, soil freezing is at its maximum, and snow melt is rapid.

Recent research in Colorado

When our research was started in the high Rockies of Colorado in 1938, it was felt that an extension of previous experiments on forests and snow was warranted for two main reasons. First, aside from the Wagon Wheel Gap study no real snow research had, to our knowledge, been conducted on these problems in the Central Rockies. As a corollary, the water yield problems of our region are of such great importance that they justify a considerable investment of research effort. And second, up to that time all western studies with which we were acquainted had been made by unrandomized comparisons of cover types already in existence. This method is commonly the only one possible, and it has yielded a large volume of fruitful results; but it is subject to some question on a scientific basis because of the unavoidable but often unrecognized bias which may creep in.

Hence we started and are continuing a variety of experiments in Colorado, especially designed to supply information on the influences of forest cover and timber cutting on water yields which are derived largely from snow.

Up to now these investigations have been confined to the Fraser Experimental Forest, near Fraser, Colorado. This area occupies a small watershed in the lodgepole pine and Engelmann spruce-alpine fir types, ranging from about 9000 to over 11,000 ft in elevation.

Studies in mature lodgepole pine--The first experiments were started in 1938, with the establishment of 20 harvest-cutting plots in mature lodgepole pine [WILM and COLLET, 1940]. These are located in a small drainage of rugged topography, with timber ranging in merchantable volume from about 7000 to 17,000 bd ft/acre (including as "merchantable" only trees larger than ten inches in diameter) and averaging 11,900 bd ft/ac. Each plot is eight ac in gross area, including an isolation strip which reduces the area actually sampled to five ac. The 20 plots were grouped into four blocks, within each of which four timber-cutting treatments and an uncut plot were distributed at random.

For the study of snow accumulation and melting rates, intensive snow surveys were made throughout the snow-melting seasons of 1938-1943, inclusive. Starting between March 15 and April 1 of each year, when the soil under the snow blanket was still dry, a sample measurement of snow depth and water content was taken near each of 500 snow stakes (25 per plot), each week until all the snow had disappeared. The water-content samples were taken by means of a Utah snow sampler [CLYDE, 1930], at first with a standard spring balance, accurate to the nearest ounce or inch of water, but later with a more precise dial-type Isoseal balance, accurate to the nearest 0.1 ounce.

Data obtained during the first two spring periods (1938-1939) served to show how snow storage and melting rates were affected by natural variations in canopy density, exposure, and other factors. Then, in 1940, 16 of the plots were cut over by selection methods so as to leave different numbers of trees and merchantable "reserve volumes" on different plots. Within each block of five plots, one was left uncut as a check; all trees larger than 9.5 inches in diameter were removed from another plot; and the rest were left with reserve volumes of 2000, 4000, and 6000 bd ft/ac. As another way of showing how intense the cuttings were, the heaviest left 143 trees larger than 3.5 inches in diameter per ac (on the average) as compared to 382 trees on the uncut plots. The other treatments left intermediate numbers of trees, roughly in proportion to the intensity of treatment.

Even before the cuttings were done, these studies indicated several interesting facts on the storage and melting of snow within this virgin forest. For one thing, the initial water content of snow (in March, before melting began) varied directly with the distance of each sampling point from surrounding trees [WILM and COLLET, 1940]. The smallest amounts of water were stored inside dense groups of trees, and the largest amounts in relatively large openings. For each foot of horizontal distance from the edge of a canopy opening, water content increased or decreased about 0.068 inch. As the holes in this uncut forest were all smaller than 60 ft in diameter, considerably less than the height of surrounding trees, the data showed no flattening of this straight-line trend even for the largest available openings.

In order to provide a combined estimate of initial snow storage and melting rates, we added together the water contents measured at each sampling point in successive weekly surveys throughout the melting season. Thus a large initial storage followed by slow melting would give a maximum value for the "storage-duration index" and low initial storage followed by rapid melting would provide a minimum index composed of only a few weekly figures, each small in size.

While such an index has rather limited usefulness, it helped illuminate the results obtained in our studies. The index was found to be correlated, for example, with canopy openings in a manner similar to initial storage. This fact would tend to indicate that high initial water content in large openings was not offset by accelerated melting, but remained high throughout the season.

Within our plots, relative exposure to sun was also found to exert an influence on melting rates, though not to any significant extent on initial storage. As shown in Figure 1, the lowest storage-duration indices were observed on southwest slopes, and the highest values on northeast slopes.

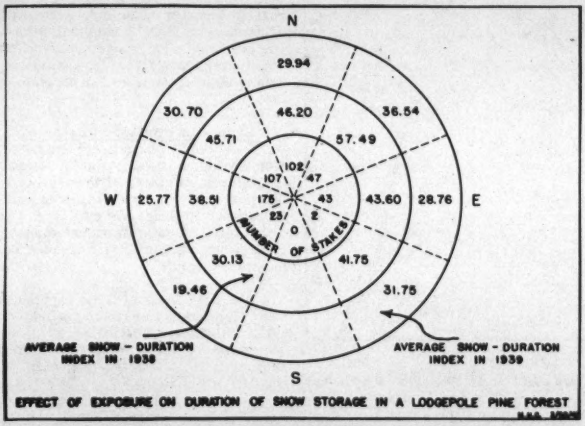

Fig. 1--Effect of exposure on duration of snow storage in a lodgepole pine forest

The results obtained in the three years after treatment indicated that timber cutting exerted a strong influence on both snow accumulation and melting rates [WILM, 1944]. Table 1 shows the initial storage of snow as observed on the plots, and also adjusted statistically (last line) to remove the effects of inherent plot characteristics, not associated with the treatment. Based on these adjusted values, the heaviest cutting resulted in a gain of about two inches of water, or about 26 per cent, over the amounts of water stored on the uncut plots; while the less severe cuttings exhibited intermediate effects.

Melting rates were distinctly accelerated by timber cutting (see Fig. 2). The increased amounts of water stored on the cut-over areas disappeared just enough more rapidly than the smaller amounts in the uncut plots, so that all the plots became bare at about the same time each

Table 1--Influence of timber cutting on snow accumulation

Year	Merchantable reserve stand, bd ft/ac				
	11,900 (uncut)	6000	4000	2000	0
	in[a]	in[a]	in[a]	in[a]	in[a]
1941	5.42	6.13	6.68	7.20	7.43
1942	6.00	6.95	7.42	8.18	8.32
1943	9.60	11.00	12.10	13.80	13.45
Average	7.01	8.03	8.73	9.66	9.73
Adjusted Average[b]	7.60	8.41	8.61	9.09	9.59

[a]Water content in inches [b]Adjusted to values that would be expected if all plots had the same exposure (compass direction) and had stored the same amounts of snow before treatment.

year. For convenience, these results are shown in Table 2 as the number of days between April 1 and the date when the last snow disappeared; the figures evidently exhibit no real effect of timber cutting.

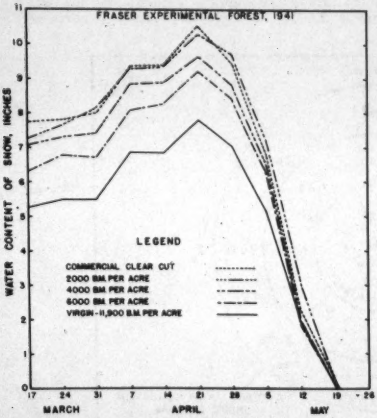

Fig. 2--Influence of timber cutting on snow accumulation and melting of snow stored in a mature lodgepole pine forest

At first glance our results seem to be somewhat in conflict with those of earlier studies, which generally indicated that snow remained longer under forest cover than on adjacent open land. Even the thin forest of our cut-over areas, however, apparently provided enough protection from wind and sun to retard melting rates as compared to unforested land.

Studies in immature lodgepole pine--While work was being conducted in mature lodgepole pine forests, somewhat similar studies were also started in stands of young second-growth pine. Because of their widespread occurrence throughout the lodgepole pine type in the Rockies and elsewhere, such immature forests present rather important problems of snow storage and water yield.

The first phase of these experiments has been reported in an earlier publication. [NIEDERHOF and DUNFORD, 1942], which is quoted briefly below to show the conditions encountered and what was learned:

> ...This particular study, begun in 1940, was designed to measure the influence of crown openings of various sizes upon snow accumulation and melt in two young lodgepole pine stands; and, from the results, to indicate the degree of cutting necessary in these young stands for maximum snow storage.
>
> The two stands selected for study are part of a large body of timber and are located adjacent to each other on a broad level bench. The first stand has an average height of 17 ft and is open grown... The average opening between trees has a diameter of 19 ft and an average of 14 trees immediately surrounding it. Because of the open character of the stand, the trees have broad full crowns extending to the ground. The second stand is both taller and denser with an average height of 23 ft. The average opening, 21 ft in diameter, has 30 trees immediately surrounding it...

Table 2--Influence of timber cutting on the duration of snow-melt (in days after April 1)

Time	Merchantable reserve stand, bd ft/ac				
	11,900 (uncut)	6000	4000	2000	0
	day	day	day	day	day
Before treatment 1938-39, Average	56	58	64	61	61
After treatment					
1941	50	50	50	51	51
1942	57	58	59	61	58
1943	54	55	55	56	54
Average after treatment	54	54	54	56	54

During the spring of 1940, 30 natural openings were selected for study in each stand, varying in average diameter from 3.8 to 44.0 ft in Stand 1 and 4.0 to 48.5 ft in Stand 2. For the 1941 measurements, three additional large openings were selected in Stand 1 and five more in Stand 2; after these were added the largest openings in each stand had an average diameter of 56 ft.

Samples of snow, expressed as water content in inches, were taken at the center of each opening and then, starting 2.5 ft from the center, at intervals of five ft to the edges of the opening in four directions: northeast, southeast, southwest, and northwest. In this way a minimum of one sample was obtained in the smallest opening, and a maximum of 25 samples in the largest.

The data obtained in this experiment indicate conclusively that snow storage and rate of melting are influenced by the size of crown openings. Due to high losses from crown interception, small openings consistently provide less snow in storage than amounts found in larger openings... the largest volumes of water in stored snow at the beginning of the melting season were found in openings with a diameter of 20 ft or more. Thus, for maximum winter accumulation of snow, heavy cutting might be indicated.

Conditions are rather different, however, where prolonged melting is desirable in addition to maximum winter accumulation. In this case, as demonstrated by storage-duration indices, crown openings between 16 and 17 ft in size appeared to provide optimum storage in this type of immature lodgepole pine (see Fig. 3)... Smaller openings provided too little initial storage; and larger openings, by their exposure to sun and wind, showed rapid rates of loss through melt and evaporation.

This first phase of experiments in young lodgepole pine served to show the influence of this kind of forest on snow storage and melt; and it indicated how snow conditions might be improved by thinning the forest canopy. With this work as a basis, more intensive studies have been started for the purpose of testing the quantitative effect of such thinnings on watershed conditions. These include 18 small plots, set up in six blocks covering a variety of sites and stand densities. Two of the three plots in each block have been thinned. A uniformly scattered stand of single trees was left on one of them, and a series of circular openings was cut on the other. In the latter treatment, each opening was about 20 ft in diameter, and separated from the adjacent openings by a thin fringe of trees. For silvicultural reasons, a single vigorous tree was left in the center of each opening to provide the eventual timber crop.

These studies are not completed; but already we have found that both thinning methods have increased snow storage and that there seems to be no real difference between the two methods. While melting rates have been accelerated by the thinnings, preliminary observations indicate that the last snow disappears at least as late in the thinned as in the unthinned plots.

Comparisons of cover types--In addition to the experiments in pine forests we have done some work in comparing the relative values of dense young pine stands, aspen, and open grassy fields as watershed vegetation. Like the preliminary studies in young lodgepole pine, the first part of these experiments (conducted from 1941 to 1943) has already been published [DUNFORD and NIEDERHOF, 1944]. Hence, it should be necessary only to quote in brief terms from this article, and to summarize the results obtained on the storage and melting of snow:

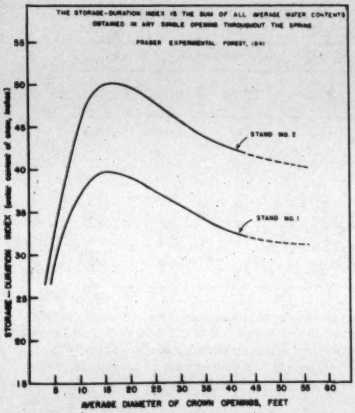
THE STORAGE-DURATION INDEX IS THE SUM OF ALL AVERAGE WATER CONTENTS OBTAINED IN ANY SINGLE OPENING THROUGHOUT THE SPRING
FRASER EXPERIMENTAL FOREST, 1941
STAND NO. 2
STAND NO. 1
STORAGE—DURATION INDEX (water content of snow, inches)
AVERAGE DIAMETER OF CROWN OPENINGS, FEET

Fig. 3--The effect of canopy openings on the accumulation and melting of snow under young lodgepole pine; the storage-duration index is the sum of all average weekly water contents for each opening

A single area of forest land at an elevation of 9000 ft provided the desired comparison of cover types. Tnis area was logged in 1910 and subsequently burned; the present cover consists of aspen and young lodgepole pine, intermixed with open grassland. On this site several contiguous units were selected for study: one area with a homogeneous cover of aspen; another with a stand of young lodgepole pine; and, adjacent to these, three grassland openings which were enlarged by clearing to provide study areas of adequate size.

For each cover type, aspen, lodgepole pine, and grass, the losses to which precipitation is subjected before it finally enters the soil were measured each year at a series of 50 randomized locations marked with five-foot stakes that could be seen above the snow, a total of 100 locations for the two years of the study. These sites were selected within areas of 5.8 ac in the aspen, 8.3 ac in the pine, and 4.3 ac in the open fields, exclusive of isolation borders.

Starting just before spring melting began, samples of snow were obtained at all 50 locations in each of the three cover types. Measurements were made at weekly intervals, starting between March 15 and 30 and continuing until the snow was gone from all three types, about May 15 to 25. Depth and water content of the snow were measured with a Utah snow tube within a radius of four feet of the stake which marked each sampling location.

Greater amounts of winter snowfall were accumulated in aspen and open grassland than in a stand of young pine. This indicates that the thick and closely spaced crowns of the young pines captured much of the snow and allowed it to be evaporated back into the air from the numerous needle and twig surfaces. Aspen, on the other hand, devoid of leaves in the winter, offered only negligible obstruction to falling snow and perhaps reduced the snow-surface evaporation by mollifying the action of sun and wind...

In the open field type, however, the absence of interception was probably partially offset by water losses from the stored snow, resulting from a maximum exposure to Sun and wind...These two possible sources of loss in the open fields may account for the fact that the aspen stand presented somewhat better conditions for snow storage, in spite of the fact that a slight degree of interception in the latter cover type prevented maximum rates of accumulation.

It was found that the rate of snow-melt was more rapid on the open fields than under either type of forest cover (see Fig. 4). From the available data it cannot be said, however, that aspen and pine differed substantially in melting rates. Both types were entirely bare within a week after the last snow had diappeared from the open fields.

These comparative studies of the three cover types, like the ones specially devoted to young and mature lodgepole pine, are being continued. While the more recent results are not ready for publication, all the evidence indicates that aspen provides very desirable watershed conditions, particularly for storing and retaining snow.

It whould be added at this point that our data on "open" land can be considered to apply only to rather small open areas in timberland. On large open areas, such as old "burns" at high altitudes, the amounts of snow accumulation and rates of loss depend largely on the degree of exposure to wind. When sheltered, they seem to provide excellent conditions for snow storage. Severely exposed areas, on the other hand, may remain practically bare of snow all winter.

Present state of knowledge

Based on all the evidence discussed on the preceding pages, perhaps we can now summarize what we have learned about the influence of forest cover on snow storage and melt

Any form of vegetation presents a mechanical barrier to the falling snow, holding back a portion on its aerial canopy. How much is held and evaporated apparently depends almost entirely on the depth and density of the canopy. Therefore the largest amounts of snow will be lost in a dense conifer forest, and the least in thin, leafless hardwood stands or on open, unforested land.

After the blanket of snow has been deposited, vegetation acts to retard further losses by either melting or evaporation. It does this by shading the ground and reducing wind movement, to an extent varying with the density and type of stand. Thus melting rates are slowed down, although the time when melting begins may not be appreciably delayed.

With these facts in mind, it can be seen that forest cover is desirable to a certain extent, but that it should not be so dense as to prevent maximum snow storage. The evidence very strongly supports Church's description of the most desirable kind of forest for snow conservation, "a fir forest possessing a maximum number of glades." It seems, too, that an aspen stand or other hardwood forest is desirable, especially if it is interspersed with clumps or areas of conifers.

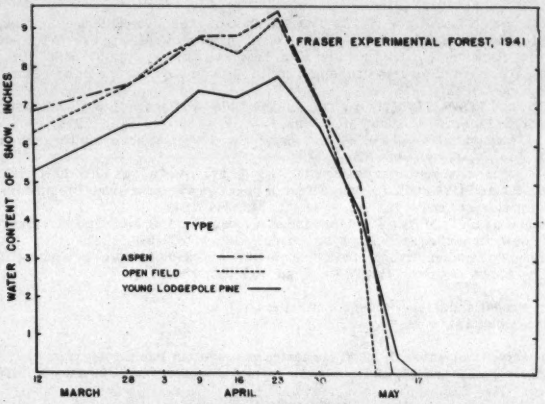

Fig. 4--Snow accumulation and melting as affected by three types of vegetation

Summary--Throughout the semi-arid western United States, water supplies depend to a large extent on the storage and melting of snow. Because much of the snow producing these supplies is deposited on forest-covered watersheds, people interested in water have long been concerned with the effects of forest vegetation on the disposition of snow. Melting rates form an important part of this problem, because they may have a direct bearing on the height and time of peak stream discharges, and on the volume and distribution of total run-off.

Past studies of snow storage and melting rates, as well as the opinions of experienced workers, vary a good deal and exhibit some conflict. In general, however, they indicate that a forest tends to retard melting rates. This was considered desirable by some writers, and undesirable by others.

Recent experiments in Colorado have, in general, borne out and extended the results of earlier studies. Because of interception, both mature and immature stands of lodgepole pine were found to reduce the winter storage of snow as compared to an aspen forest and open, grassy areas. In both kinds of pine forest, snow storage was increased by timber cutting.

Offsetting this greater winter storage, melting rates were greater on open land than in aspen and the pine stands; and they were accelerated by timber cutting. Under all the forest canopies studied, melting started at about the same time in the spring: Around the middle of April or somewhat later. From then on, higher melting rates under the thinner canopies and in open areas tended to consume the greater volumes stored under these conditions, so that the last snow disappeared at about the same time or even earlier than in heavy forest.

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DISCUSSION

Walter U. Garstka (U. S. Bureau of Reclamation, Denver, Colorado)--It has been a priviledge to read this scholarly presentation of the influence of forest cover on snow-melt. I recall attending, years ago, meetings at which the subject was argued pro and con with emotional fervor but with a sad deficiency of basic information. Papers such as this serve to present the subject in truer perspective, so that the numerous technologists interested in watershed management can base their thoughts on facts known to date.

The forest influences investigations of the Rocky Mountain Forest Experiment Station in the headwaters of the Colorado are being followed with interest by hydrologists and engineers. Water supply for irrigation and multiple-purpose usage is measured at certain definite points along a stream channel. Increased storage of snow expressed as water equivalent produced by the reduction of crown density can be expected, reasonably, to increase water yield.

It should be kept in mind, however, that the microclimatological process of snow accumulation on a soil surface and the physical process of conversion of water from a crystalline to a liquid phase, otherwise known as snow-melting, are but two stages in the hydrologic cycle of streamflow resulting from snow precipitation.

Runoff-producing effectiveness of a snow pack is affected by many factors. One of the major factors is that of soil moisture deficiency resulting from evapotranspiration losses suffered during the preceeding dry season. Since ecologists recognize that a vegetal cover tends to utilize all available soil moisture irrespective of density of the stand, reduction of the forest reserve by removal of certain percentages of trees cannot be expected to result in reduction of soil moisture loss. On the contrary, opening of the crown canopy may produce conditions favorable to herbaceous and shrubby vegetation. This growth may result in a possible increase in transpiration losses of soil moisture. Ground cover vegetation may utilize water which, in its absence, could have been available for tree growth. One can only conjecture whether water yield from increased snow storage is or is not balanced by increased soil moisture loss. It could develop that, if increased transpiration losses did not exceed extra water yield from the reduced tree density, that the reduction of available water for tree growth could result in reduction of rate of growth of the forest trees, thus reducing timber yield, but prolonging the snow storage effectiveness of the treatment.

To be of practical significance, the net effects of forested watershed management must be evaluated in terms of streamflow as measured at some point of utilization along a stream channel. Water-supply engineers are looking forward to the results which can only come from an extensive watershed application of the very interesting and promising observations which have come from the Fraser Experimental Forest.

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REVIEW OF CURRENT HYPOTHESES OF ORIGIN AND TECTONIC SIGNIFICANCE OF SCHISTOSITY (FOLIATION) IN METAMORPHIC ROCKS

Francis J. Turner

The nature of schistosity

In the fabrics of most metamorphically deformed rocks some degree of parallel alignment of planar or linear fabric elements is evident. Such rocks are said to be schistose or foliated. Although these two terms have been used in different senses by some writers [HARKER, 1932], in this paper schistosity and foliation are defined synonymously to include all parallel fabrics of metamorphic origin which impart megascopic fissility to the rocks in which they occur. This definition, like Sander's use of the descriptive term s-surfaces to cover similar phenomena [SANDER, 1930, pp. 97-99], avoids the difficulty which arises when genetic terms like "flow cleavage" and "fracture cleavage" are applied to structures whose origin may be impossible to demonstrate by ordinary field and petrographic observations.

While schistosity is related to the presence of sub-parallel, more or less plane surfaces in the fabric, the term "lineation" is reserved for that component of the fabric which is determined by parallel linear elements such as crystal axes, intersections of s-surfaces or axes of microfolds [CLOOS, 1946].

Characters of rock fabric that are very generally associated with schistosity are as follows:

(1) Dimensional parallelism (preferred orientation according to crystal form) of platy and prismatic crystals of such minerals as micas, chlorites, amphiboles, epidotes. This was once thought to be the main controlling factor in schistosity [LEITH, 1913, pp. 78-79], and certainly is one of the most obvious.

(2) Alignment of mineral cleavages parallel to the schistosity (for example, micas, chlorites, talc) or to the lineation (amphiboles, epidotes).

(3) Almost universally a preferred orientation of all essential minerals according to space-lattice structure. This condition first clearly demonstrated by Austrian petrologists [SANDER, 1930], applies just as much to irregular grains of quartz, calcite, and plagioclase as to tabular and prismatic crystals of mica, hornblende, and others. It would therefore seem to have a more fundamental significance than the more obvious preferred orientation according to external form, or the alignment of cleavages noted under (2).

(4) Approximately plane surfaces of rupture or weakened cohesion which have developed during deformation. TYNDALL [1856, pp. 44-45] and BECKER [1904, p. 11], who produced "slaty cleavage" in wax, and allied substances by laboratory deformation, attached great importance to this factor in schistosity.

(5) Laminated structure resulting from segregation of contrasted mineral assemblages into alternating bands parallel to the schistosity (for example, quartz-albite bands alternating with muscovite-chlorite layers in mica schists [TURNER, 1941].

Mechanical and chemical processes involved in evolution of schistosity

Microscopically recognizable effects of stretching, bending, plastic deformation, rupture, and displacement of mineral grains in metamorphic rocks are familiar to every petrographer, and testify to the general effectiveness of purely mechanical (cataclastic) processes in deformation of rocks. These are grouped together by SANDER [1930, pp. 115, 269-275] as direct componental movements. It is equally clear that chemical processes (indirect componental movements) such as solution, ionic migration, and crystallization must have played an important part wherever metamorphism involves general increase in grain size (for example, in conversion of mudstone to mica schist) or appearance of new minerals (for example, garnet, staurolite, actinolite). While it is

recognized that metamorphism typically is a long, drawn-out complex process in which both direct and indirect componental movements participate, it is proposed now to review separately some of the individual mechanisms that are involved.

Development of surfaces of slip and rupture in the rock fabric--A rock deformed under high confining pressure in the presence of chemically active pore fluids may yield slowly without loss of cohesion. Permanent deformation of this kind has been described loosely as "plastic flow" as contrasted with failure of brittle materials by rupture. There is, however, no sharp distinction between flow and fracture of polycrystalline aggregates such as rocks. And the anology between plastic behavior of rocks and of metals is somewhat loose in view of the fundamental difference between ionic and metallic crystal lattices. Plastic flow of rocks typically involves rupture of the component crystals, and differential movements on slip planes within the fabric; but on the whole recrystallization keeps pace with rupture, and fractures are healed fast enough for the rock to maintain an essentially coherent condition.

BECKER'S [1893, 1904, and 1907] classic attempt to identify schistosity with major slip surfaces and to correlate these with the circular sections of the strain ellipsoid need not be reviewed here. His hypothesis, based on mathematical analysis of stress and elastic strain in a homogeneous body, has been justly criticized as being incapable of exact application to plastic deformation of heterogeneous rocks. Nevertheless Becker's hypothesis has great petrologic significance; for it emphasizes the relation of schistosity to slip surfaces whose orientation is determined at least partly by the distribution of stress in the deformed body. Sander and Schmidt, using the technique of petrofabric analysis, independently reached conclusions that agree in many respects with those of Becker [SANDER, 1930, pp. 97-101, 218-219]. They attach great importance to schistosity originating parallel to slip planes, but recognize that it is not the only type of schistosity commonly occurring in deformed rocks. Sander also emphasizes the common tendency for slip movements to occur along mechanically weak s-surfaces already present in the parent rock, rather than on planes of higher shearing stress along which the strength of the rock may also be greater. This would explain the commonly observed coincidence between schistosity and bedding in schists derived from sedimentary rocks.

Plastic deformation of rocks, even under high confining pressure, will not proceed indefinitely, but ultimately leads to rupture [GRIGGS, 1936]. Among the various factors which favor ruptural as opposed to plastic deformation are reduction of confining pressure, slowing of chemical activity, as under reduced temperatures, and long duration of the deforming process. It is not surprising therefore to find that rocks whose deformation has been accomplished largely or partly by plastic flow are traversed by large-scale or microscopic shear and tension joints formed during the later stages of deformation. The pattern of such joints is typically related to that of schistosity and lineation, so that joints may conveniently be classified according to their relation to the references axes of the fabric. (The principal plane of schistosity is conventionally identified as the ab plane of the fabric, with the c axis normal to it; b is defined genetically as the axis normal to the principal directions of deforming movement, and is thus parallel to contemporaneous fold axes, and in many cases coincides with most prominent lineation in ab.) Tension joints (Q-joints, ac-joints) nearly normal both to the schistosity and to lineation of the b type are very common. h0l-joints also are developed by shear parallel to the b axis of the fabric. Closely spaced h0l fractures, or partially healed slip surfaces, impart to the rock a type of fissility (schistosity) sometimes distinguished as strain slip or fracture cleavage. It has often been assumed that this must necessarily be the imprint of a later deformation than that responsible for the main schistosity; but this is by no means necessarily the case.

Behavior of individual grains--The mechanical response of an individual grain to the forces imposed on it as the rock deforms is some combination of internal plastic yielding, rupture, and rotation of the grain as a whole. From the kinematic standpoint a grain may be said to have reached a stable position when frictional resistance to rotation is greater than the externally applied shearing stress (a couple acting in some particular direction). If the latter exceeds the internal resistance to crystal gliding, however, then the grain may deform by plastic flow, that is, by translation or twin gliding on some plane and in a direction of weakness in the crystal lattice. If this mechanism has played an important role in deformation, one or both of the following features may be expected in the rock fabric:

(1) Alignment of crystal glide planes and glide lines parallel respectively to principal surfaces and directions of slip in the fabric. Strong aligment of visible deformation lamellae in calcite and in quartz may safely be correlated with the existence of corresponding slip planes in the fabrics of some rocks. But possibly too much emphasis may have been placed upon orientation of crystallographic glide planes as a general explanation of the preferred orientation of mineral lattices in deformed rocks.

(2) Dimensional orientation of grains elongated by internal gliding, with their longer dimensions in the AB plane of the strain ellipsoid. Note, however, that it cannot be assumed that deformation necessarily was brought about by compression perpendicular to AB of the ellipsoid. Nor can the above generalization apply to cases where the elongated or tabular form of grains is the result of crystallization, not internal deformation. Thus the validity of SHARPE'S [1849] conception of slaty cleavage attributed to flattening of the component grains under a simple compression, is at least highly doubtful.

Passive rotation of grains presumably occurs when the frictional resistance on the external surface of a grain is exceeded by the applied shear force. Some of the effects attributed by various writers to this mechanism are as follows:

(1) Elongated or tabular rigid crystals embedded in a plastically flowing matrix develop a strong dimensional orientation with their longer axes in the AB plane of the strain ellipsoid [SANDER, 1930, pp. 149-150; KNOPF and INGERSON, 1938, pp. 133-135]. Slaty cleavage has been interpreted on this basis by many writers since SORBY [1856] first published the results of his experiments in this field.

(2) Orientation of crystal glide planes in principal slip planes of the fabric is believed by most writers on petrofabrics to be achieved partly through preliminary rotation of grains into a position favorable for gliding [SCHMIDT, 1932, pp. 174-176].

(3) The common patterns of preferred orientation of quartz according to space-lattice structure have been attributed by SANDER [1930, pp. 173-178], GRIGGS and BELL [1938], and FAIRBAIRN [1939] to rotation and dimensional alignment of splinters produced by rupture of larger grains. A necessary condition is that there should be some regular relationship between the long dimensions of the fragments produced by rupture and the space-lattice structure of the mineral in question. The experiments of GRIGGS and BELL [1938] show that under some conditions quartz ruptures into fragments having a marked tendency to be elongated parallel to the c-axis, the unit rhombohedron or the basal plane.

(4) Grains which possess neither tabular habit nor potential crystallographic glide planes are apparently committed to continual rotation when surrounded by a plastically flowing matrix. The classic instance is garnet, porphyroblasts of which commonly enclose spiral trains of inclusions as evidence of prolonged rotation.

Role of crystallization--Most schists are coarser in grain than the rocks from which they have been derived. Moreover, most of them consist largely or partly of minerals newly formed during metamorphism. In all such cases crystallization, either broadly contemporaneous with deformation (paratectonic), or continuing after deformation (post-tectonic), must have played a significant part in evolution of the rock fabric. From a physico-chemical standpoint the growth of crystals in a heterogeneous anistropic solid medium is highly complex, and its effects correspondingly difficult to predict. Stable minerals form at the expense of minerals less stable under prevailing physical conditions in the particular chemical environment provided by the pore fluids. Moreover, the individual grains of a single mineral vary in stability, so that some grains persist and develop while others are eliminated. Factors which tend to decrease stability are small grain size, irregular outline, local application of stress on the crystal surfaces, strained condition of the crystal lattice, and presence of impurities within the grain concerned. In the anistropic growth medium afforded by a rock cut by regularly oriented slip surfaces and micro-fractures, the crystallographic orientation of a grain in relation to the rock fabric is probably an important factor in determining whether the grain will survive or will be suppressed. This influence is clearly illustrated in the case of vein minerals.

Faced with this highly-complicated problem some of the ablest students of metamorphic fabric, while emphasizing the important role of crystallization in fabric evolution, restrict their discussion to strictly mechanical processes such as those enumerated earlier in this paper [SCHMIDT, 1932, p. 171]. Others have interpreted schistosity almost wholly in terms of one of the many factors involved in crystallization. Such, for example, is Riecke's principle, which has been so generally invoked as the explanation of schistosity, that it cannot be omitted from a discussion such as this.

For current opinions as to the applicability of Riecke's principle, the reader is referred to GRUBENMANN and NIGGLI [1924, pp. 167-170, 463-464]; BOYDELL [1926, pp. 12-22]; HARKER [1932, pp. 144-145]; KNOPF [1933, pp. 460-461]; ESKOLA [1939, pp. 282, 283, 294, and 295]; GORANSON [1940]; FAIRBAIRN [1942, pp. 42, 43, and 55]. If a crystal immersed in a solvent

is elastically strained by a compressive or a tensile force applied to a pair of opposite faces, its solubility now varies from face to face according to the uneven distribution of resultant stress over the crystal surface. Under ideal conditions a crystal thus stressed will dissolve over its whole surface, and complementary crystallization will take place in unstressed areas of the fabric. But if the pore solution is capable of sufficient supersaturation, simultaneous solution at the highly stressed surfaces and outgrowth from the less stressed surfaces of the same crystal are possible, and it could then develop an elongated or flattened form.

Riecke's principle might well be a contributing factor in the development of a single schistosity marked by parallel alignment of tabular or lensoid grains normal to a simple compressive force [ESKOLA, 1939]. But the rock in question should be much coarser than the parent rock, and any pattern of preferred orientation of constituent minerals should be symmetrical about the axis of compression, that is, the normal to the schistosity. Most schists depart strikingly from these requirements. Commonly occurring instances of such departure include the following:

(1) Any rock whose average grain size is notably coarser than that of the parent rock, for example, all pelitic mica schists; quartz schists derived from cherts; coarse amphibolites derived from basalts; (2) the great class of B-tectonites, with preferred orientation conforming to a girdle pattern symmetrical about a line (B-axis) within the plane of schistosity; (3) any rock in which minerals such as quartz, calcite, and faldspar show a pronounced space-lattice orientation pattern, but no correlated tabular or prismatic habit. It would seem then, that crystallization governed by Riecke's principle is probably much less effective as a factor in the evolution of schistose fabrics than was at one time generally thought to be the case.

SANDER [1930], ESKOLA [1939, p. 294], and other modern students of fabric attach considerable importance to the tendency for crystals to grow with their longest dimensions aligned in planes and directions of maximum ease of growth in the rock fabric. In crystals of most metamorphic minerals certain crystallographic directions may be identified as axes of most rapid crystal growth (for example, the c axis in actinolite; directions normal to the c-axis in mica and in calcite). Crystal nuclei that happen to be oriented with the preferred direction of growth in a slip surface or other fabric plane offering minimal resistance to crystal growth, survive and develop at the expense of less favorably oriented grains. Paratectonic or post-tectonic crystallization governed by this principle gives rise to a state of preferred orientation of the crystal lattice as well as of external form. A familiar instance is the development of radial aggregates of amphibole prisms parallel to the foliation of garbenschiefer. Post-tectonic crystallization acting on the same principle (mimetic crystallization) may transform the fracture cleavage of a phyllite or a phyllonite into a crystallization schistosity indistinguishable from typical flow cleavage formed by paratectonic crystallization.

Another possible factor in paratectonic crystallization, but one whose effects on the fabric are still impossible to assess, is the influence exerted by the stress pattern upon the relative stability of crystals oriented at random within the stressed field. If crystals of a given mineral, for example, calcite, are markedly anisotropic with respect to such properties as compressibility, solubility, or resistance to shearing stress, then the stability of a given crystal should presumably be affected by its crystallographic orientation with respect to the principal directions and planes of stress within the deforming rock. It has been suggested, for example, that with a field subject to simple compression, grains of calcite that happen to be oriented with the c axis (direction of maximum compressibility) parallel to the direction of compression are relatively stable, and hence grow at the expense of grains differently oriented [BAIN, 1938, p. 17]. It is likewise conceivable that grains having a crystal glide plane parallel to a plane of high shearing stress in the rock fabric may persist and ultimately come to dominate the fabric on account of their relative stability compared with that of other grains.

In the absence of adequate experimental data, any statement as to the relative influence of the many factors involved in crystallization upon the ultimate fabric of the metamorphic rock would be unjustified speculation. Nevertheless, from the complex and perhaps unpredictable process of crystallization at length emerges a fabric the symmetry and pattern of which almost invariably conform to one or another of several clearly recognizable types. This is compatible with the hypothesis advanced by Sander and generally accepted by workers in the field of petrofabrics, that the various mechanisms of crystallization and the associated direct componental movements are coordinated under the influence of the stress plan of deformation, to give a unified movement picture. The symmetry of this picture and hence of the governing stress plan is assumed to be reflected in the symmetry of the tectonite fabric. Only in relatively rare simple cases, for example, in some mylonites and slickenside films, can this assumed relation between symmetry of fabric and symmetry of the movement plan be demonstrated clearly.

Types of schistosity in relation to deforming forces and movements

General statement--Correlations between schistosity and deforming forces and movements figure prominently in the literature on tectonics of metamorphic terranes [TURNER, 1942; WILSON, 1946]. It is not necessary here to trace the growth of ideas on this problem. Nor is it proposed to review the conflict that developed between rival hypotheses. Nevertheless it is interesting to note that many geologists are still reluctant to abandon the convenient assumption that schistosity is a simple structure capable of interpretation in terms of some universally applicable principle. Three fundamentally different hypotheses, each of which is still accepted by one or another school of geologists as being universally applicable to schistosity in general, are outlined below:

(1) By SHARPE [1849] and SORBY [1856], and various modern writers [HARKER, 1932, pp. 153-155, 193-195; BEHRE, 1933, pp. 53-55], schistosity is attributed to a compressive force acting normal to the schistosity plane.

(2) Petrologists of the Wisconsin school [for example, LEITH, 1937, p. 364; MEAD, 1940, p. 1010] have interpreted flow cleavage as invariably lying parallel to the AB plane of the strain ellipsoid. The axis of maximum shortening is thus identified as the normal to the plane of schistosity.

(3) According to BECKER [1907], schistosity surfaces are essentially planes of minimum cohesion determined by slip parallel to surfaces of high shearing stress in the deformed mass. Among modern European writers SANDER [1930, pp. 97-101] and SCHMIDT [1932, pp. 199-203] recognize the importance of schistosity of this type. Schmidt even believes that the most conspicuous set of s-surfaces (schistosity) in any deformed rock can be identified as the principal set of slip planes active during deformation.

Most writers who have investigated the schistosity problem from the standpoint of fabric analysis believe that none of these hypotheses should be either universally applied or totally rejected as an explanation of schistosity. On the contrary, they tend to recognize several distinct types of schistosity each capable of subdivision on the basis of fabric criteria. Some of the characteristic features of each type are outlined bleow.

Type 1: Schistosity parallel to slip planes--In regions such as the European Alps, where alpine folding and regional metamorphism have been active together, rock deformation has been accomplished largely by differential movement on closely spaced slip planes that now survive as schistosity. In many cases slip has occurred principally along surfaces of mechanical weakness afforded by bedding; so that schistosity commonly parallels bedding and conforms to the configuration of contemporary flexural folds. In regions of recumbent folding and low-angle thrusting, schistosity of this class may maintain a gently dipping or sub-horizontal attitude over large areas. Substantially horizontal schistosity is thus no certain criterion of load metamorphism.

In some rocks of this class, for example, in many mylonites and phyllonites, a single schistosity, identified as the ab plane of the fabric, predominates. More commonly there are several sets of slip surfaces intersecting in a lineation (b fabric axis) parallel to contemporary fold axes. This lineation may even be so prominent as to dominate the whole fabric, and the rock then breaks into elongated pencils rather than into slabs.

The symmetry of fabric is monoclinic. In other words, all elements in the fabric conform to a single plane (ac) of symmetry. Typically there is a strong lineation (b) normal to the symmetry plane and defined by microfolding of schistosity surfaces, intersection of slip surfaces, and parallel alignment of prismatic and tabular crystals or of elongate mineral aggregates. But lineation parallel to a, and thus lying within the symmetry plane, may also be present, and in slickensided and mylonitized rocks may completely overshadow the b lineation [CLOOS, 1946].

Conspicuous girdle patterns about the b axis are highly characteristic of orientation diagrams for most minerals in schists of this class. This applies especially to diagrams showing orientation of the c axis of quartz or calcite, and the poles of $\{001\}$ in micas and $\{01\bar{1}2\}$ lamellae in calcite. The stronger the lineation parallel to b, the more pronounced is the girdle pattern of orientation diagrams and the monoclinic symmetry of the fabric as a whole.

Tension joints roughly normal to b may be useful in confirming the identity of lineation parallel to b.

Type 2: Schistosity normal to compression--Schistosity correlated with flattening under compression, as between the jaws of a vise, is widely distributed, especially in pre-Cambrian terranes. It commonly dips steeply, indicating subhorizontal compression, and approximates to the axial planes of contemporary flexural folds.

Typically, the rock splits evenly along a single set of schistosity planes (ab of the fabric) marked by subparallel alignment of mica flakes and flattened lenses of quartz, calcite, or feldspar. Lineation parallel to b may not be present, but in any case is a less conspicuous element in the fabric than the schistosity. Where present, lineation is caused mainly by dimensional orientation of prismatic and tabular crystals.

Many rocks of this class have a symmetry of fabric which is described as orthorhombic, in that there are mutually perpendicular symmetry planes ab, bc, and ac. The quartz fabric may, however, show triclinic symmetry conflicting with the orthorhombic symmetry of other elements in the fabric. Constituent minerals show patterns of preferred orientation dominated by the ab plane, with the influence of h0ℓ planes, presumably symmetrically developed slip planes, often clearly recognizable in addition, particularly in the quartz fabric. Girdle patterns typically are weak or incompletely developed compared with those characteristic of the preceding class.

Other types of schistosity--On theoretical grounds a third type of schistosity is to be expected, with fabric characters which might be identical, in different cases, with those of either one or other of the two types just described. The most conspicuous kind of schistosity is that marked by subparallel orientation of tabular crystals of mica and allied minerals. This is shown equally well by schistosity due to slip (Type 1) and by schistosity correlated with compressional flattening (Type 2). In the former case orientation could develop by alignment of $\{001\}$ glide planes, or by growth of tabular crystals, in the slip planes of the fabric. In the second type the controlling mechanism could be crystal growth governed by pressure or rotation of passive tabular crystals embedded in a plastically flowing medium, toward an equilibrium position with $\{001\}$ parallel to the AB plane of the strain ellipsoid. It has yet to be proved that during deformation of quartz-mica rocks the mica crystals actually do rotate passively in this manner. However, if this is one of the important orienting mechanisms, it must ultimately lead to preferred orientation of tabular crystals subparallel to AB of the strain ellipsoid, regardless of the nature of the deforming force or movement [SANDER, 1934, p. 141]. The general result would be a fabric in which schistosity S_1, coinciding with AB of the strain ellipsoid would be intersected obliquely by slip planes S_2 which might or might not be sufficiently conspicuous to constitute a second set of schistosity planes. In such a rock the schistosity S_1 would neither coincide with possible slip surfaces, nor would it necessarily have developed normal to a compressive force.

In cases of strong deformation involving differential movement on one set of slip surfaces S_2, these would ultimately be rotated so as to intersect the AB plane of the ellipsoid (schistosity S_1) so obliquely that the two would merge to give a compromise schistosity approximating to Type 1 described above. On the other hand, where several sets of slip surfaces S_2, S_3 . . ., have been active and their arrangement with respect to AB of the ellipsoid (S_1) is fairly symmetrical, the condition characteristic of Type 2, with AB normal to a compressive force, is closely approached.

Concluding statement--Until more experimental data are available regarding development of oriented fabrics under controlled conditions, correlation of schistosity with deforming forces and movements will still be attended by some degree of ambiguity. In the meantime we recognize that schistosity may be correlated alternatively with slip surfaces or with the AB plane of the strain ellipsoid. In the majority of cases fabric criteria are much more compatible with one correlation than with the other. Where schistosity is identified with the AB plane of the ellipsoid, it does not necessarily follow that deformation was the result of simple compression acting normal to this plane; but a close approach to this condition is probable in the case of flattened rocks with orthorhombic symmetry of fabric.

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NOTE ON THE TECTONIC SIGNIFICANCE OF DEFORMATION LAMELLAE IN QUARTZ AND CALCITE

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Statement of the problem--All petrographers are familiar with the tendency for quartz, calcite, and certain other minerals to show a microscopic lamellar structure when they occur as constituents of strongly deformed rocks. Moreover there is convincing evidence that the structure is itself due to deformation, a process of crystal gliding either by translation, twinning or both. Use of the general term "deformation lamellae" seems amply justified. It is not proposed to review this evidence here, since it has been dealt with adequately in a number of recent accessible papers in which the approach is from the petrofabric standpoint. For discussion on lamellae in calcite the reader is referred to SANDER [1930, pp. 202-206]; KNOPF and INGERSON [1938, pp. 163-166]; GRIGGS [1940, pp. 1005-1007]; for quartz to HIETANEN [1938, pp. 31-38]; FAIRBAIRN [1941]; INGERSON and TUTTLE [1945]; and RILEY [1947, pp. 461-468]. Several of these writers suggest that the mechanims of gliding whereby the lamellae originated may also have been responsible for the condition of preferred orientation of space-lattice displayed by the quartz or calcite grains in which the lamellae occur.

The purpose of this paper is to raise a question for discussion, rather than to solve a problem. In a deformed rock where quartz, calcite, or some other mineral shows well-developed deformation lamellae and also a strong preferred orientation of the space-lattice, are these two characters of the fabric necessarily directly related, or may they be partly independent? Moreover, what is the significance of the lamellae orientation pattern in constructing the movement plan of rock deformation in such cases?

The degree and pattern of preferred orientation of quartz or calcite according to space-lattice structure, is conventionally demonstrated by orientation diagrams based upon measurement of optic axes in a sufficient number of representative grains. A more complete picture may be obtained in the case of calcite by plotting the poles of all three planes of the form $\{01\bar{1}2\}$ for each grain; or alternatively all three horizontal crystal axes, as located graphically from the relative positions of the c-axes and measured lamellae $\{01\bar{1}2\}$ or cleavages $\{10\bar{1}1\}$, may be plotted. This has rarely been attempted however, [FELKEL, 1929]. But deformation lamellae by virtue of their visibility, are more impressive than the invisible directons of the optical indicatrix. On this account we have perhaps been prone to emphasize unduly the development of deformation lamellae as a mechanism leading to the evolution of observed space-lattice orientation of quartz and calcite in tectonites. This emphasis on the mechanical as contrasted with the chemical aspect of deformation of quartz in particular cases is illustrated by the following quotations:

"Excellent orientation relations of the deformation lamellae and crystal axes indicate the control of the quartz orientation by the lamellae rather than by the axes. A translation hypothesis is considered to explain the relations best" [FAIRBAIRN, 1941, p. 1265].

" If the lamellae really represent planes along which quartz has been plastically deformed, and if they tend to form approximately normal to the c-axis, whatever the reason, then they may provide at least part of the explanation of how preferred orientation of the c-axes of quartz is developed in deformed rocks." A mechanism of combined rotation and gliding is then outlined [INGERSON and TUTTLE, 1945, p. 103].

"The degree of preferred orientation of the (quartz) lamellae in the Otago rock is noticeably higher than that of the optic axes measured in the same grains, a fact which suggests that the observed orientation of the quartz lattice has been controlled by movements on the lamellae rather than by gliding parallel to prism faces" [MACKIE, 1947, p. 366]. (The present writer had discussed this particular case with Mackie, and at that time agreed with this as a possible interpretation of the fabric.)

These opinions reflect one of several alternative ways in which the petrofabric data may be interpreted. However, another possibility, which the writer considers more generally applicable, is that the visible lamellae express only the very latest phase of rock deformation. On this assumption, where the pattern of space-lattice orientation is clearly related to that of the deformation lamellae in the same mineral, it is likely that the space-lattice orientation developed first and is the more fundamental character of the tectonite fabric.

The role of indirect componental movement--Indirect componental movements such as solution, ionic diffusion and recrystallization must have played an important, if not the dominant, role in deformation in all cases where new metamorphic minerals have crystallized during rock deformation. The same holds good where deformational metamorphism involves notable increase in grain-size, as when mudstone is converted to mica schist, or limestone to coarse marble. When deformation lamellae are conspicuous in quartz or calcite of such rocks they can only be assigned to a very late stage in deformation; and to consider the development of space-lattice orientation in such cases in terms of purely mechanical movements (rotation and gliding) is to over-simplify what must have been a complex process. As an instance may be cited coarse-grained quartz-piedmontite-muscovite schists from western Otago, New Zealand, in some of which MACKIE [1947] has recorded well oriented deformation lamellae in the quartz grains. These rocks have been shown to be metamorphic derivatives of manganiferous cherts [TURNER, 1946]. The main constituent, quartz, now occurs in the form of intricately interlocking elongate coarse grains averaging 0.2 mm to 0.5 mm in diameter. Like the associated piedmontite and muscovite the quartz shows a strong preferred orientation of space-lattice the pattern of which conforms to that of schistosity and lineation in the same rock. It is at least highly probable that solution and recrystallization, clearly responsible for eliminating the great majority of original small quartz granules, have dominated the process by which a state of preferred orientation of space-lattice has developed in the final coarse-grained product. The conspicuous deformation lamellae now visible in most of the quartz grains must reflect the latest, and possibly only a subordinate, phase of deformation. The clear relation between the orientation patterns of lamellae and optic axes in some of these rocks can readily be understood, if it be assumed that the stress pattern which controlled the evolution of lattice orientation in its later stages continued on unchanged during the final phase in which deformation lamellae orignated.

Deformation lamellae in quartz--As first suggested by FAIRBAIRN [1941], deformation lamellae in quartz are probably irrational surfaces of translation the majority of which cut the c crystal axes at high angles (greater than 60°). But it is also clear that lamellae also develop, though not so freely, at lower angles of inclination, and may even be parallel to the c-axis. Crystallographic control of the plane in which lamellae may develop in a given grain is thus comparatively light. It is therefore not surprising to find, in nearly all recent accounts, that the pattern of preferred orientation of deformation lamellae tends to be much more sharply defined than that of accompanying preferred orientation of optic axes. From this condition it has sometimes been inferred [FAIRBAIRN, 1941; INGERSON and TUTTLE, 1945, p. 103] that the space-lattice orientation is controlled by the more sharply defined lamellae pattern, and that the latter more accurately expresses the movements and stresses involved in rock deformation. To the present writer it seems equally possible that the lattice orientation developed first, and that in the last stages, when chemical activity had waned, the lamellae developed parallel to planes of maximum shearing stress. (This line of reasoning does not presuppose any particular mechanism, either mechanical or chemical, of development for orientation of space-lattice.) The preference for translation to occur on planes steeply inclined to the c-axes of favorably oriented grains accounts for the obvious relation between patterns of diagrams based on axes and lamellae, respectively. The freedom for translation to occur to a less extent on planes subparallel to c accounts for the sharper definition of the lamellae pattern.

Perusal of recent literature suggests that some degree of divergence or incompatibility between the orientation pattern of quartz lamellae and the pattern of other elements in the fabric, (such as foliation, lineation, and mica orientation), is the rule rather than the exception. Thus in the sheared quartzite from the Ajibik formation investigated by FAIRBAIRN [1941], the quartz lamellae conform sharply to a movement pattern involving slip on two sets of fabric planes symmetrically inclined to the single strong foliation. FAIRBAIRN [1941, p. 1271, Fig. 4] correlates these movements with simple compression normal to the foliation; but this latter structure would seem to have resulted from strong differential movement within the foliation plane itself. These two patterns of movement and stress are incompatible. In the Baraboo quartzite, RILEY [1947] finds that the clearly defined pattern of the quartz lamellae is unrelated to either bedding, foliation, or the pattern of quartz axes in the same rock. He concludes therefore that the deformation lamellae which he observed in quartz grains reflect movements subsequent to the main deformation responsible for the schistosity.

In his account of the New Zealand quartz-piedmontite-muscovite schist referred to earlier in this paper, **MACKIE** [1947, p. 365] records rare instances in which a deformation lamella in one grain of quartz is continued on into adjacent grains as a lamella of somewhat different orientation. Such lamallae could develop only after the grains in question had assumed their present position, that is, they must express the latest phase of rock deformation.

A puzzling feature is a remarkable consistency of the orientation pattern to which the deformation lamellae in quartz grains conform in almost every described instance. The lamellae diagrams recorded by **SANDER** [1930, p. 306, D21], **FAIRBAIRN** [1941, p. 1268, Fig. 1], **INGERSON** and **TUTTLE** [1945, Fig. 2], **MACKIE** [1947, Fig. 9], and **RILEY** [1947], for quartz in rocks of widely different geographic situation, age, tectonic environment and fabric, all show the quartz lamellae alined in two planes intersecting at angles of 60° to 90°. It is tentatively suggested from this evidence that development of deformation lamellae in quartz is favored by simple compression (as in a vise), with consequent relatively slight differential movement upon surfaces of maximum shearing stress so induced.

Deformation lamellae in calcite--The calcite grains of almost any coarsely crystalline marble show lamellae developed to a greater or less degree. These are generally believed to be twin lamellae due to twin gliding parallel to one of the three planes of the flat rhombohedron $\{01\bar{1}2\}$. **FELKEL** [1929], **SANDER** [1930, p. 202], **FAIRBAIRN** [1942, p. 63], and others consider that pure translation on $\{01\bar{1}2\}$ without accompanying twinning may also be effective in causing deformation lamellae to appear in calcite. With this view the writer agrees. In a recently investigated marble from Yule Creek, Gunnison County, Colorado, only a minority of observed lamellae could be shown definitely to be due to twinning; while more than half are probably, though not certainly, products of simple translation.

There are several ways in which orientation patterns of calcite lamellae may be interpreted in a reconstruction of the movement and stress plans of deformation. Some of these are illustrated by examples below.

GRIGGS [1940, pp. 1006-1007] found that when a coarsely crystalline marble was compressed in the laboratory under high confining pressure with a resultant shortening of the test specimen by 30 per cent deformation lamellae became very conspicuous. He describes the resultant "twinning" as being "more intense than that in many natural marbles which we know have been more drastically deformed." Accompanying features in the fabric of the artificially deformed rock are strong preferred orientation of c crystal axes parallel to the compressive force and obvious cataclastic microstructure [**GRIGGS**, 1940, pl. 2, Fig. 2]. In this case, and hence presumably in some cases where naturally deformed marbles have an obviously cataclastic fabric, preferred orientation of the calcite space-lattice has been accomplished by mechanical means (direct componetal movement). The relative importance of crystal rotation and internal gliding has not been determined. **FELKEL'S** [1929] classic study of calcareous tectonites from the Austrian Alps includes petrofabric analyses of several marbles whose fabrics appear to reflect essentially mechanical deformation. The deformation lamellae in these rocks are alined parallel to one or more slip planes of the fabric [**SANDER**, 1930, D. 69-85].

In many marbles the grains are more or less equant and are bounded by intricately interlocking surfaces, while the only visible effect of direct componental movement is the widespread presence of deformation lamellae. Recrystallization has probably played an important, and perhaps the principal role in deformation of these rocks. However conspicuous the deformation lamellae may be, it seems probable to the writer that the space-lattice orientation of the calcite grains has been determined at least partly by recrystallization. Alternative ways in which the preferred orientation patterns of such rocks may be interpreted are noted briefly as follows:

(1) By some combination of mechanical rotation and recrystallization the individual grains have assumed a state of preferred orientation with potential glide planes parallel to planes of high shearing stress in the rock fabric. Translation or twinning on the glide planes so aligned has now caused their visible development as deformation lamellae. Orientation diagrams constructed respectively for poles of lamellae and for the glide lines (edges between $\{01\bar{1}2\}$ lamellae and $\{10\bar{1}1\}$ as deduced from relative positions of the c-axis and the observed lamellae, reflect the movement and stress plans of the deformation evolved.

(2) Rather rarely it may be possible to demonstrate an early origin for deformation lamellae in calcite. Among the Alpine marbles described by **FELKEL** [1929] are some (for example, that from Vennatal [**SANDER** 1930, D. 78-83])in which only the larger grains of calcite show deformation lamellae. These are aligned parallel to the foliation and are believed to express an early

phase of metamorphism. Associated smaller equant grains without lamellae are correlated with later static recrystallization in the course of which a completely different state of space-lattice orientation developed. The c-axes of the recrystallized grains are aligned subparallel to the foliation, while those of the relict lamellar grains intersect the foliation at high angles.

(3) A third possibility is that orientation of optic axes is related to recrystallization during the principal phase of deformation. Deformation lamellae developed during a later, usually subordinate strain. This condition is illustrated by the fabric of certain Vermont marbles described by BAIN [1938] who attributes orientation of the c crystal axes of calcite grains to difference in compressibility of calcite as measured parallel and perpendicular to the c-axis respectively. Yule marble, recently investigated by the writer, affords another illustration. In this rock the c crystal axes show well defined preferred orientation approximately normal to the foliation. Orientation diagrams for deformation lamellae $\{01\bar{1}2\}$ show strong maxima whose positions appear to be determined largely by pre-existing orientation of the optic axes; but there is also a distinct though weak girdle pattern independent of the optic axes pattern and expressing a relatively late strain. An additional indication that some lamellae in this rock are of late origin is the manner in which individual lamellae in one grain pass continuously into corresponding lamellae of somewhat different orientation in adjacent grains.

(4) There is also the possibility that some or all of the observed lamellae may express a late strain of no tectonic significance. This is to be suspected either when late lamellae show a preferred orientation pattern that can be accounted for completely by observed pre-existing orientation of the calcite axes; or in the case of those lamellae whose orientation departs markedly from a well defined pattern shown by lamellae of other grains in the same rock. These "non-tectonic" lamellae may originate in either of two ways. They may represent the response of the rock to stresses set up during the period of cooling and unloading that intervenes between metamorphism and exposure of the rock at the surface. Recent work has shown that stresses set up during alternate heating and cooling of metals and alloys through a range of a few hundred degrees have been most effective in causing deformation lamellae and other strain structures to develop in the microfabric [BOAS and HONEYCOMBE, 1946 and 1947]. The controlling property appears to be aristropy with respect to thermal expansion, a property which calcite and many other minerals possess to a marked degree. Finally there is the disconcerting possibility that the late strain responsible for at least some lamellae has developed during grinding of the rock section. In this latter case preferred orientation patterns of lamellae should differ markedly in sections of different orientation cut from the same specimen. Calcite responds so readily to shearing stresses of relatively low magnitude, that we may expect to find in almost any section of marble at least some lamellae which have originated in one or other of the two ways just mentioned. While they, like $\{10\bar{1}1\}$ cleavages, have no direct tectonic significance, they are usueful enough in bringing out any pattern of space-lattice orientation that may be present in the fabric. Such an orientation pattern is demonstrated by measuring and plotting the positions of the c-axis and the visible lamellae or cleavages, and determining graphically the positions of poles of the remaining lamellae or cleavages of the same form, regardless of whether or not they are visibly developed.

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PRELIMINARY REPORT CONCERNING THE RESEARCH ON SHORT-PERIOD MICROSEISMS AT SAINT LOUIS UNIVERSITY

J. E. Ramirez

Abstract--The work of seismologists on the various microseismic frequencies ranging from one minute to thousandths of seconds is briefly summarized, and a description is given of the present status of the short-period (0.2-0.5 sec) microseismic research sponsored by the Office of Naval Research, with special emphasis on the new tripartite station set up at Florissant, Missouri.

Microseismic band spectrum of frequencies--It seems advantageous to present a picture of the natural ground oscillations called microseisms in terms of a band spectrum of their frequencies. However, no one seismometer will be able to give us a full view of the total spectrum. Any given seismograph acts more or less as a band-pass filter and will show to best advantage those waves whose periods correspond most closely to the free period of the pendulum. The more the wave periods depart from the free period of the seismograph, the more those waves tend to be filtered out.

An experiment performed March 30, 1938 by the author showed how microseisms may be spread over a whole scale of periods. Four electromagnetic seismometers of the same type, and recording side by side, were set to record microseisms at different periods, more or less in resonance with the galvanometric periods. The recording was made on the same paper wound around the same drum. The Macelwane-Sprengnether seismometers used, had the following periods: Seismometer 1, 2.2 sec; seismometer 2, 6.1 sec; seismometer 3, 15.0 sec; seismometer 4, 38.0. The corresponding galvanometers were: 1.3 sec Moll type, made by Kipp and Zonen, Holland; 6.1 sec Leeds and Northrup Type R; 15.0 sec Leeds and Northrup Type R; and 38.0 Leeds and Northrup Type HS.

The four seismographs picked up microseisms of different periods, but the largest in amplitude were those of the 6.1 sec period combination.

The first microseismic "color" that attracted the attention of investigators, was that of periods ranging between four and eight sec, which included the common periods of the early seismometers. These microseisms are surface waves traveling over oceanic and continental paths and are invariably caused by low air-pressure areas moving over the ocean [RAMIREZ, 1940].

During World War II, the tripartite-station method was used by the United States Navy for the purpose of tracking tropical cyclones over the ocean, thus avoiding the exposure of warships, convoyts, and transport airplanes to the danger of shipwreck by sailing into the track of unreported hurricanes.

After the War, the number of Navy tripartite stations was steadily augmented both in the Caribbean Sea and in the Pacific Ocean.

Early seismologists, for example, MILNE [1908, Chaps. 19, 20, and 21] and GALITZIN [1910], recognized a long period, irregular type of microseisms with periods of about 20 to 40 sec registered by the long-period seismograph then in use.

Another microseismic color, or band of frequencies, toward the lower end of the microseismic spectrum is found in the 15- to 20-sec period range. These are often registered by the very long-period seismographs and have been found also in the Corpus Christi microseismic records. According to R. R. Heinrich (oral communication), in the past two years these microseisms at Florissant have appeared especially strong in the winter months. The wave form on the St. Louis records is not always as regular as that of the ordinary four- to eight-sec period microseisms.

Going up towards the higher frequencies there are microseisms in the one and three sec range as recorded by the short-period Sprengnether-Macelwane seismometer and Moll galvanometer at St. Louis, by the Benioff short-period seismograph at Bogotá, and elsewhere and by the Sprengnether seismometers at Corpus Christi.

These microseisms probably correspond to one of the types described by GILMORE [1946]. These waves are rather regular in form and although the traffic vibrations seem to interfere with them in some localities during the day, they appear continuously and clearly during the night. Special studies to these microseisms are being carried out by the Fordham seismologists.

Around 1930 J. B. Macelwane noticed and commented to seismologists and instrument makers on the very regular microseisms of a period from 0.2 to 0.5 sec, appearing daily in the records of the Wood-Anderson short-period seismometers both at the St. Louis University Gymnasium and at the Florissant vault. Some years later H. Benioff on a visit to St. Louis discussed with Macelwane this microseismic band and pointed out that their origin could not be instrumental as he had thought, since they were recorded also at Pasadena.

These short-period microseisms characterized by tneir fine wave form, long series of waves, and exceedingly low amplitude increasing at times to about two mm in the ordinary earthquake records, are the object of this special research problem.

CARDER and GILMORE [1945] have also written on the dominant periods of these high-frequency microseisms in specified localities. They report periods between a little over 0.5 and 0.15 sec.

Four more bands of higher frequencies in the microseismic spectrum should be mentioned. One band in the 0.05-sec frequency range appears very prominently in the Corpus Christi records of the former Naval tripartite station. In October 1947, the author, in going over these records, was so much impressed by the new type of wave period that he secured from Gilmore three sample records of this type to be studied at St. Louis University. At the suggestion of Macelwane, it was considered worthwhile to initiate a special investigation covering a time interval of several months. A good series of records have been kindly furnished by Gilmore and the study has been entrusted to V. J. Jennemann, a graduate student at the St. Louis University Institute of Technology. Jennemann has also found (oral communication) in the Corpus Christi records average periods of 0.8 and 1.3 sec besides those mentioned already.

It should be noted that the Corpus Christi tripartite microseismic station rested upon several ft of very fine sand, a geologic feature which might be responsible for the very short-period ground motion. A similar period of microseismic waves recorded by a station located on the Island of Sylt in Germany has been reported with periods of the order of 0.02 sec [BELENSIEFER, BUETTNER, PFLEIDERER, and WETZEL, 1939].

Furthermore, microseisms of still higher frequencies have been reported by geophysical crews working with sensitive geophones. Frequencies of around 0.01 sec have been registered sporadically in the already mentioned Corpus Christi records and superimposed on the lower frequency microseisms according to Jennemann.

Finally in his investigations of the rock vibrations resulting from the impact of falling water at Queistalsperre, GRUNMACH [1913] found the dominant periods to be about 0.005, 0.008, and 0.029 sec.

The specific problem--The present investigation has been directed to the study of the nature and origin of the 0.2-0.5 sec period microseisms, as exemplified by using the method devised by the author under the direction of Macelwane in 1938 (see Fig. 1).

The tripartite station--The grounds of the Florissant seismograph station, which are far from railroad and automobile traffic and about 17 mi from St. Louis University, were chosen as the best location for the tripartite station. One corner of the triangle was established at tne Florissant seismic vault (see Fig. 2), the second corner is approximately 600 ft due northeast and the third corner is about 800 ft due northwest of the Florissant vault.

Piers of concrete (of rich mixture: 1 cement, 2 sand, and 3 stone) have been constructed at the second and third corners. They are buried one foot below the ground and project two ft above the ground in the form of an L (the longer side of the L is 60 inches in length, and shorter side 47 inches in length and both sides have a width of 18 inches).

Around each cement pier a wooden frame has been erected with four poles embedded in concrete four ft deep. A double cover of waterproof rock wool has been placed between the empty spaces of the double wall and ceiling to prevent temperature changes. An aluminum corrugated roofing covers the sheathing on top. The structure which is shown in Figure 3 is eight ft long and eight ft wide. The height is also eight ft at the front and six ft at the back.

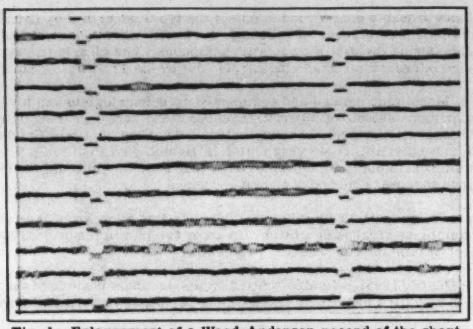

Fig. 1--Enlargement of a Wood-Anderson record of the short-period microseisms; the interval between time marks is one minute

Fig. 2--Looking down on the main Florissant vault in 1927 before the excavation was filled in; the nearer projection is the ventilator shaft; the farther projection is the staircase of which the opened door may be seen at the left

Fig. 3--One of the two subsidiary vaults of the new tripartite network

The instruments--Each one of the tripartite stations will be equipped with three components of the capacity seismograph type (see Figs. 4 and 5), one Benioff short-period microbarograph and one Macelwane longer-period microbarograph.

Galvanometer bank and tape recorder--A 12-galvanometer bank has been designed, partly constructed, and some tests have been carried out. It consists of a compact unit of 12 small and specially designed galvanometers of the D'Arsonval type with free periods of 0.3 sec in resonance with the microseisms. They record side by side on a tape recorder contained in the same box. The tape recorder will carry photographic paper 12 inches wide

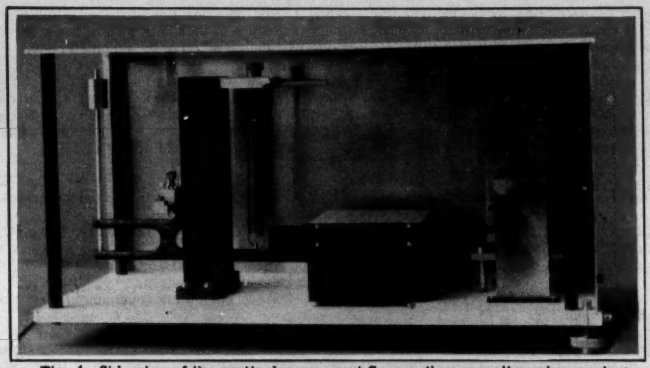

Fig. 4--Side view of the vertical-component Spregnether capacity seismometer; the Volk amplifier pickup will rest on top

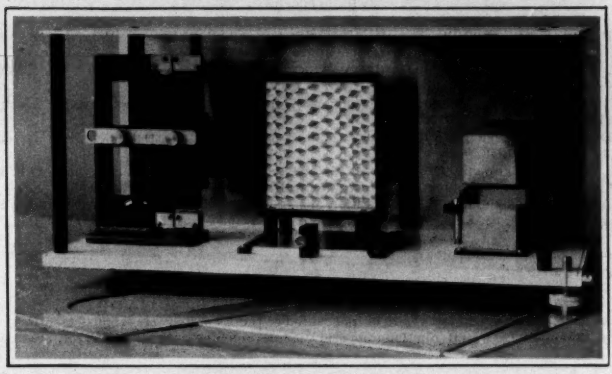

Fig. 5--Side view of the horizontal-component Sprengnether capacity seismometer; the Volk amplifier pickup will rest on top

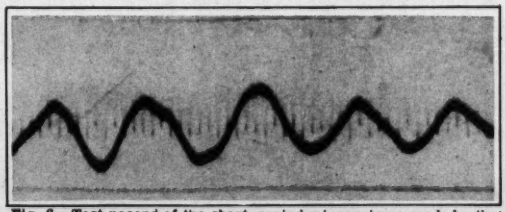

Fig. 6--Test record of the short-period microseisms made by the new horizontal capacity seismometer; the interval between time lines is 1/50 sec

at speeds of three, five, or ten cm/sec, changeable at will. The duration of the runs will be limited by a time-switch mechanism to one minute every quarter of an hour. Nine of the galvanometers will be connected to the nine capacity seismographs and the other three galvanometers to the three short-period Benioff microbarographs.

The microbarographs--Besides the three short-period Benioff microbarographs located at each corner of the tripartite station, there will be three Macelwane-Sprengnether microbarographs registering on a triple drum at a normal speed of 60 mm/min. The light source may be turned off part of every hour so as to space the lines of the record farther apart if necessary.

The seismometers--At first it was intended to construct seismometers with very high magnifications (about half a million times) as part of this project. However, it was found advisable, on several grounds, to make use of a high-gain capacity pickup device, already developed for general purposes by Joseph Volk of the Department of Engineering of St. Louis University. Using this pickup, the seismometers have the desired magnification and seem to be the type we want for this purpose. A detailed description of this pickup will be published later by Volk.

Figure 6 is part of a test record showing the 0.2-0.5 sec period microseisms recorded by the new seismometer.

Acknowledgments--The work covered by this report was done by J. B. Macelwane, F. Robertson, J. E. Ramirez, J. Volk, C. Kisslinger, and W. F. Sprengnether, Jr., at St. Louis University, and was under contract with the Office of Naval Research.

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RESEARCH IN OCEANOGRAPHY AT THE WOODS HOLE OCEANOGRAPHIC INSTITUTION DURING APRIL 1947 TO APRIL 1948

C. O'D. Iselin

During the past year, much of the effort at the Woods Hole Oceanographic Institution has gone into field observations. Increased operating costs and commitments for scientific salaries make it impossible any longer to finance our research vessel Atlantis from endowed income. Thus her continued employment has depended on funds provided by the government and by grants from scientific societies. It has been our feeling that the primary need in oceanography is still for more and better observations, rather than for theory or the study of old data. We have, therefore, emphasized field work in the expectation that it might soon have to be sharply curtailed.

During April and May 1948, the Atlantis completed the network of deep hydrographic stations she had begun occupying the previous autumn in the area between Cape Hatteras, Bermuda, and Puerto Rico. A total of 189 stations is now available from this roughly triangular sector. These are arranged in ten parallel north-south profiles. In the course of this work many other useful data were secured.

There followed a two weeks' cruise beginning late in June 1948, in which a detailed study was made of a large eddy south of the Gulf Stream in the sector off the Gulf of Maine. This work was under the direction of Frederick Fuglister. Then during the period July 15-September 15, under a grant from the National Geographic Society, Maurice Ewing and his assistants carried out a geophysical reconnaissance of the Mid-Atlantic Ridge in the area just south of the Azores.

October and November 1948 were devoted to a complete overhaul of the Atlantis and for the installation of much new equipment. The fuel capacity was increased and a relatively large deep-freeze food locker was installed in order to make it practical to undertake surveys at greater distances from Woods Hole than has been the custom in the past. Early in December the Atlantis left Woods Hole on a cruise of seven months' duration from which she has not yet returned. The objective is a general oceanographic survey of the Mediterranean. Martin J. Pollak is in charge of the scientific party of nine.

Two trends have become very clear during the past year. In areas where navigation by Loran is favorable, as along the track of the Gulf Stream, it is now possible to study the details of the current pattern. Frequent Loran fixes provide a good record of the speed and direction of the surface current. The bathythermograph provides a convenient means of observing the temperature distribution down to a depth of 300 m associated with these currents. Thus without stopping the vessel, the currents and the temperature structure can be tracked on the basis of the incoming information. The oceanographer is relieved of the disadvantages of following a fixed pattern of observations and he can intelligently alter the course of the vessel so as to observe best the effects under study. The importance of this technique cannot be over-emphasized.

The second trend in oceanographic field work is also due to instrumental developments. A variety of instruments is now able to supply continuous information. The recording, deep echo-sounding machine is one example. The temperature-salinity recorder is another. Thus, each day the vessel is at sea she accumulates many more data than was possible in the past. This increased efficiency in the observational program more than counteracts the increased costs of operating. It also very much adds to the labors of the scientific party, not only because of maintenance, but also because continuous watches have to be established to monitor the various instruments.

In addition to the Atlantis surveys in deep water, the Institution has operated several other vessels in coastal waters. From April to December the USS Mentor was operated off the coasts of Texas and Louisiana for the United States Geological Survey. In this operation, radar was first used as a means of accurately locating offshore-gravity stations. Wherever buoys can be set out, this technique is convenient and perhaps a simpler method than the Shoran type systems.

The Balanus and the Reliance, which are roughly 70-foot fisherman-type vessels, have been operated near Woods Hole, mainly in connection with instrumental development. The latter vessel is government-owned and at the request of the Office of Naval Research was recently turned over for one year to the University of North Carolina for use by the new Institute of Fisheries Research.

Our laboratory has been a busy place during the past year, the great majority of the work being carried out under contract with the Government. It is not easy to summarize this program and it will only be possible here to mention some of the studies which seem to be of special significance to the geophysical sciences.

Submarine geology--With the assistance of a grant from the Geological Society of America, Henry C. Stetson, Fred B. Phleger, and Parker Trask have been busy examining the large collection of bottom cores secured last winter from the Gulf of Mexico. These studies are not only of considerable geological interest, but they also promise to present the physical oceanographer with a whole new series of problems. We have been content to study the temperature and the circulation of the ocean as it exists today, but in the sediments in deep water is an undisturbed record of the main features of the ocean extending back over a long period of time. When different climatological conditions prevailed over the oceans, what were the currents and how did the general distribution of temperature differ from that found today? Much of this history of the ocean can probably be worked out through a study of cores of the deep sediments.

New observations of the total thickness of the unconsolidated sediments on the floor of the ocean provide material for another important study. J. B. Hersey and Maurice Ewing have been collaborating closely on collecting such data and some preliminary reports of their results will be published shortly. This type of measurement will have to be continued as a routine on oceanographic vessels for many years before the full potentialities can be realized. It is important to note that they have been successful in recording the arrival of echoes from several thousand ft below the bottom without having to stop the vessel.

Chemistry of sea water--Gordon Riley and B. H. Ketchum and their assistants have been developing the chemical approach to the general problem of the productivity of the sea. Riley has been mainly studying the available chemical data over wide areas from the standpoint of plankton production. Ketchum has been particularly concerned with the distribution of phosphate compounds along the margin of the continental shelf from Cape Hatteras northeastward in order to work out the seasonal cycle of the movement of these nutrients and to learn whether or not any mechanism exists in this area to return nutrients from considerable depths to the surface layer.

Alfred C. Redfield has begun a study of the oxygen data from the same area and is having success in using the oxygen-density correlation to identify sources of various water masses in which the temperature-salinity correlation shows too little variation.

Marine meteorology--Through a contract with the Office of Naval Research, the work under which is directed by Bernhard Haurwitz, it has become possible to institute a rather long-range attack on some of the problems where marine meteorology may be expected to differ somewhat from meteorology over the land. Theoretical studies, instrumental development and field observations are proceeding hand in hand. Andrew Bunker has been devoting particular attention to means of gaining better measurements of the heat and water vapor exchange between the sea surface and the lower layer of the atmosphere. Alfred H. Woodcock has concentrated mainly on methods of measuring the size distribution and number of salt nuclei in the air over the ocean. Raymond B. Montgomery has recently undertaken a theoretical study of fog formation over the sea. These may seem to be rather isolated projects, but in actual fact they have a certain unity when combined with other studies which have not been specifically mentioned.

Development of oceanographic instruments--Under this heading comes a considerable volume of somewhat thankless but important work being supported by the United States Bureau of Ships. The practical difficulties with oceanographic instruments are many and to improve them is by no means easy. Nevertheless, because of the present high costs of operating research vessels and the vast volume of data needed, if we are ever to be able to describe the oceans at all completely, a considerable effort in instrumental development is warranted. As already mentioned, instruments which can record continuous information help to make the field work more efficient. Through instruments which present the data in a form convenient for analysis, or better still, carry out all the preliminary steps in the analysis, the costs of the laboratory work are reduced. We are working in both these directions with various degrees of success.

A description of the salinity-temperature-depth recorder will be published shortly. It must also be admitted that a more accurate and much simpler model seems to be surviving the test stage. A refined version of the salinity-computing circuits gives promise of competing with chlorine titration in routine salinity determinations. While these developments continue, the earlier models are going into actual field use.

I will mention only one more instrument and since this is mechanical rather than electronic, it has a fair chance of surviving the test of hard service. A. F. Spilhaus has completely redesigned the sea sampler. It now carries 12 water bottles which trip on the way up, rather than on the way down. It has been streamlined to the point where it can be used at the full speed of most oceanographic vessels. The depths at which the bottles trip can be easily changed. A description of this most useful instrument will be published shortly.

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RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL 1947 TO APRIL 1948

G. F. McEwen and Staff

Emphasis is placed on the activities within the fields of submarine geology and physical and chemical oceanography, although extensive researches within the biological fields are carried on at the Scripps Institution of Oceanography.

Tracking storms by forerunners of swell--Walter Munk has worked out relationships for computing the travel time and distance of a storm from the characteristics of swell observed at the shore station. The paths for storms computed from wave records compare favorably to those shown on the weather maps.

Wave action on structures--Munk has developed equations for estimating the forces and moments exerted by waves on vertical cylindrical beams.

Critical wind speed for air-sea boundary processes--Munk has summarized observations of rapid changes in the character of certain boundary processes at a wind speed of about 6.5 m/sec. These abrupt changes are related to the hydrodynamic character of the sea surface which has been described by Rossby and Montgomery. The change in character of the sea surface is also related to the Kelvin-Helmholz criterion for the instability of small waves in the presence of a shear.

Dynamic aspects of the equatorial current changes--Sverdrup and Reid have re-examined the dynamic aspects of the Equatorial Current changes. In the eastern Pacific they found that observed conditions can be accounted for by an application of the equations of motion involving the following forces: pressure gradients, Coriolis force, and wind stress applied at the sea surface.

Variability in direction of wave travel--R. S. Arthur has computed the growth of waves moving at an angle with the wind by generalizing the wave forecasting relationships of Sverdrup and Munk. Results agree with forecasting experience, and with observations made off San Clemente Island and the Island of Sicily.

Hawaiian swell from January 2-5, 1947--Unusually high swell from a storm 500 mi north of the islands caused damage estimated at $2,000,000 during this period. Although the waves were described as the highest in 45 years, the study by Arthur shows that existing forecasting methods give accurate values of wave height at least 24 hr in advance of occurrence. The situation affords an unusual opportunity for checking a revised travel-time relationship.

Revised wave-forecasting graphs and procedure--Arthur has completed the preparation of forecasting graphs based on the revised forecasting theory given by Sverdrup and Munk in Wind, Sea, and Swell, H. O. Pub. No. 601. Procedures have been revised on the basis of recent experience and research.

Diffraction of water waves by breakwaters--J. A. Putnam, of the Department of Mechanical Engineering, University of California, Berkeley, and R. S. Arthur have made application of a solution of the water wave-diffraction problem of Penney and Price to diffraction by a semi-infinite impermeable breakwater. Results from tank experiments verify the general form of wave-diffraction theory.

Sea surface-temperature variations influencing fog formation in Southern California--D. F. Leipper has discussed the relative importance of factors and processes affecting sea-surface temperature. Suggestions are made for predicting short period changes in the pattern of sea-surface isotherms with particular emphasis being given to the necessity for considering the initial temperature-depth structure. Evidence is presented to show that the sea-surface temperature is an important factor in fog formation in the San Diego region.

Forecasting coastal fog--Leipper has defined three non-diurnal indices in such a manner that fog will not form in the San Diego area unless these indices fall within certain critical ranges. The indices are related to the physical processes by which fog forms. They have been checked statistically over a three-year period and only one brief fog occurrence was found with the indices outside the critical range. The indices are height of the inversion base, which must be less than 1300 ft for fog to form; the temperature difference between the sea surface and the air at the altitude of the maximum temperature on the morning radiosonde, where the air temperature must be the higher; and the temperature difference between the sea-surface temperature and the afternoon surface dew point, where the dew point must not be more than 9°F below the sea temperature if fog is to form within 24 hr.

Area studies--Leipper, in conjunction with W. W. Wood, has prepared a report entitled Temperature and Salinity of Philippine Waters. He has carried out a preliminary study Sea Temperature in the Hawaiian Island Area which is being enlarged and completed by E. R. Anderson.

He has made an Analysis of Bathythermograms for Operation Highjump. This analysis was made with Luis Capurro, Lt., Argentine Navy, and Estil Hamill, Capt., AAF Weather Service, and includes heat budget and temperature-distribution studies, a note on internal waves in the Antarctic, and a summary of processes affecting the melting point of sea water.

Several thousand sea-temperature measurements made by the bucket method in shallow water along California beaches were studied to determine the diurnal variation and the relation to offshore temperatures of these surf-zone values.

Studies of sea and swell--Two statistical studies of sea and swell conditions were made by E. R. Anderson, W. V. Burt, W. C. Thompson, and J. F. T. Saur, Jr., using weather data and the wave-forecasting procedure. A Statistical Study of Wave Conditions at Four Sheltered Areas was prepared for the United States Navy and A Statistical Study of Wave Conditions at Five Open Sea Localities along the California Coast was prepared for the United States Engineer Office, Los Angeles.

The method of using the wave-forecasting procedure and past weather charts to obtain statistical wave data has been described by Wayne V. Burt and J. F. T. Saur, Jr., in an article to be published in an engineering journal.

Analysis of ships' surface-current observations--The development and use of certain statistical parameters obtainable from ships' surface-current observations were investigated by J. C. Armstrong and W. W. Wood in an attempt to devise a more rational method of using ships' observations of currents in the preparation of current charts. The use of probability ellipses to indicate the net transport of water in a given region and the pattern of the fluctuations of the net transport was proposed and a model current chart covering the area 0°-20°N, 115°-130°E was prepared using this method. The final report prepared by D. W. Pritchard due to the departure of the original authors is as yet unpublished pending comment by Armstrong.

Objective approach to the construction of streamlines of current flow--A system for the objective construction of streamlines was considered by D. W. Pritchard, so that for a given current distribution, as defined by the average current vectors, only one set of streamlines would be defined. Because the vertical velocity field can be considered negligible, the horizontal velocity field was considered non-divergent and the stream function was applicable. By proper choice of the constants of integration two sets of linear stream function fields obtained by numerical integration of the North and South velocity components become equal and the complete stream function field is defined. The method was tested for two areas and the results were encouraging.

Wind stress-analysis of the North Pacific--Saur has carried on a large amount of statistical work in the Current Section to determine the resultant average wind-stress field in the North Pacific Ocean, and a similar project is being started for the North Atlantic Ocean. The procedure involves computing the resultant stress for each five-degree quadrangle from the wind roses printed on the Pilot Charts of the given ocean.

Theory of wind driven currents--Saur has carried on further investigations of the effects of different wind-stress distributions and boundaries upon currents. This is based upon recent work by H. U. Sverdrup, indicating the close relation between the stress field and permanent ocean currents.

Daily temperature and salinity observations of the sea surface--Daily observations of sea-surface temperature and daily collected water samples have been obtained from five localities on the California Coast, exclusive of those taken at the Scripps Institution pier. The salinities of the samples have been determined by the specific gravity method. Other observations of surface temperatures have been obtained from the United States Lighthouse Tenders Sequoia and Lupine, and from tuna boats. The cooperation of organizations and personnel is greatly appreciated.

Oceanographic observations on the E. W. Scripps Cruises of 1941--The detailed results of these cruises, prepared by H. U. Sverdrup and the Staff of the Scripps Institution of Oceanography have been published in a 160-page report.

Large horizontal eddies in the upper fifty meter ocean layer off Southern California--Results of investigations by G. F. McEwen of large counter-clockwise eddies so prevalent between a northward inshore current and a southward offshore current in this region are being prepared for publication. Convincing evidence from the formulation and solution of dynamical problems suggested by these eddies supports the thesis that an observed series of eddies during a period of several months is a succession of stages of the expansion and decrease in velocity of the initial intense and relatively small eddy.

Investigations in submarine geology--These investigations under the direction of F. P. Shepard have included: (1) Longshore currents and their relation to wave trains and submarine topography; (2) observations with a new multi-sock sediment trap; (3) direct observations and photographing by a diver, Frank Haymaker, of the precipitous and even overhanging canyon walls; (4) soundings showing the intricate gully pattern at the head of several of the canyons in the Southern California area; and (5) a survey along the Hawaiian coasts revealing the definite existence of submarine canyons off the deeply eroded Pali Coast of Oahu and Molokai.

Investigations in chemical oceanography--Work under the direction of N. W. Rakestraw included the design and construction of instruments for chemical work at sea, the study of oxygen consumption in sea water over long periods, and the study of arsenic in sea water, and the tolerance of marine organisms of it. Further extension of studies on the decomposition of organic matter in the sea is in progress.

Investigations of marine plankton--These investigations, under the direction of Martin W. Johnson, may be listed as follows: (1) Study of the deep scattering layer as related to plankton and other pelagic animals that undergo diurnal vertical migrations; (2) studies of the distribution and production of zooplankton in the offshore waters; (3) seasonal fluctuations and life histories of inshore plankton animals; and (4) further analyses of plankton observations made during Operations Crossroads.

Scripps Institution of Oceanography,
University of California,
La Jolla, California

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UNITED STATES COAST GUARD ACTIVITIES IN OCEANOGRAPHIC WORK AND PLANS FOR THE FUTURE

J. F. Farley

This year the Coast Guard oceanographic program in connection with International Ice Patrol has been reactivated on a full scale basis. The oceanographic vessel, fully equipped and staffed, has already begun its observational program in the Grand Banks area to construct the first dynamic current chart in that region since before the War. Throughout the ice season periodic oceanographic surveys will be made of the most critical of the ice-infested regions. The surface-current maps resulting from these surveys are used immediately by the patrol cutters, and the Commander International Ice Patrol at Argentia, Newfoundland, to plan ice scouting by sea and air, and to predict ice movement. As usual the results of this research will be published in the annual report of the Ice Patrol. Coast Guard Bulletin No. 32 International Ice Observation and Ice Patrol Service in the North Atlantic Ocean, Season of 1946, which covers 1942 to 1945 also, has already been distributed. Bulletin No. 31, for 1941 is still in preparation.

The oceanographic vessel this year is the CGC Evergreen, a 180-ft, 1025-ton steel vessel. It is powered by a diesel electric plant of 1000 HP giving her a top speed 13.5 knots. The maximum draft is 14 ft.

The oceanographic equipment including two heavy duty oceanographic winches, BT winch and boom, and Nansen bottle racks, are mounted on the after deck about 13 ft above the water. A complete laboratory is situated one deck below the weather deck on the port side. It is about ten ft × 20 ft and contains an electrical salinometer, titration equipment, standard water, working tables, and storage space. Both winches carry about 6000 m of wire and are therefore capable of surface-to-bottom stations anywhere in the region usually under study.

The usual methods of obtaining and working up the data are used. Salinities are routinely determined by electrical conductivity method and are checked at stated intervals by titration. The dynamic heights are computed concurrently with the taking of the observations, working 24 hr a day, so that about 24 hr after the last scheduled station the completed surface map is ready for the patrol vessel. The study of other aspects and the deeper layers is left for later consideration.

The scientist in charge of the scientific program is Floyd M. Soule who is on the Evergreen and who is assisted this year by H. H. Carter, Lieut. (jg), USCG, who recently completed the post-graduate course in physical oceanography at Scripps Institution of Oceanography. Three technicians are assigned to assist the oceanographers in addition to the regular ship's complement.

The oceanographic vessel, Evergreen, is a larger and more capable ship than was formerly employed. It will provide a steadier platform and has longer cruising radius and higher speed. It should be possible, therefore, depending on the situation at the time, to either cover a larger area each survey or to complete an equal area more rapidly, thus increasing the number of maps made. This is admittedly a very small step toward the goal of obtaining a synoptic picture but it is hoped that through the use of new instruments the realization of more nearly simultaneous observations may soon be had. The Coast Guard, because of its great interest in, and immediate practical need of, these new methods is participating in the development work both financially and in making field tests.

In order to study the observed fluctuations in the current systems in the ice regions and the annual sea-ice and iceberg crop it has been the practice in the past to make a post-season ice observation and scientific cruise to the source regions of the ice and ice-bearing currents in the Grand Banks area. The most important part of these cruises is oceanographic survey. The detailed plans for 1948 have not been made but the same general lines of investigation will be followed as in the past.

Cooperative programs in the field of oceanography with other agencies will be continued as practical by Coast Guard vessels and shore stations. This includes the taking of bathythermograph

observations by the ocean weather station vessels, coastal current surveys, wind, sea, and surf data, collection of sea-water temperatures, swell observations, and field tests in underwater sound.

United States Coast Guard,
Washington, D. C.

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OCEANOGRAPHIC ACTIVITIES OF THE U. S. COAST AND GEODETIC SURVEY

Leo Otis Colbert

The interests of the United States Coast and Geodetic Survey in oceanography are well known among the many scientific societies dealing with the physical characteristics of the ocean. These interests relate principally to depths of the water, character of the bottom, rise and fall of the tide, and the study of currents. Associated with these interests are studies of the physical properties of sea water as expressed in terms of density, salinity, and temperature.

In carrying out the function of surveying and charting our coastal waters, the Coast and Geodetic Survey has constantly improved on its techniques for gathering the data, resulting in better knowledge of the ocean floor, both quantitative and qualitative.

The past several years have proven the importance of electronics in those hydrographic operations which require good coordination and accuracy of position. We have passed the experimental stage in the use of Shoran. Floating Shoran base stations have been proven feasible for the development of offshore shoals or for the strengthening of Shoran fixes where ground stations are inadequate. Shoran has been used to locate buoys which in turn were used to extend surveys by visual control or for special examinations.

Shoran equipment has been installed for the first time in small launches and used for the survey of detached dangers and as floating Shoran base stations. During the past year approximately 19,000 sq mi of Shoran-controlled hydrography was accomplished in the Western Aleutians, and about 1000 sq mi off the New Hampshire coast.

Because Shoran is limited in its practical range to distances of 50 to 75 mi, the Bureau has developed a new electronic system, which combines the accuracy of Shoran with longer range characteristics. This equipment is known as the Electronic Position Indicator. The system is particularly applicable for surveys off low coastline. During the past year, by the use of this equipment, the ship Hydrographer accomplished 15,000 sq mi of offshore hydrography in the Gulf of Mexico. Within the area of the work, distances of 225 nautical miles from the shore stations were obtained. The indications are that much greater distances are possible. The Electronic Position Indicator will be made available to our operating units as rapidly as possible. The system has completely superseded the Radio Acoustic Ranging method formerly used by the Survey for offshore hydrographic surveys.

The Survey made hydrographic surveys in other areas of the United States, including the Atlantic seaboard, and in certain of our inland waters, such as San Francisco Bay, the Columbia River at Coulee Dam, in Roosevelt Lake, and the reservoir pool above Bonneville Dam. In Alaska, in addition to the work in the Aleutians, surveys were made in Sitka Sound, Prince William Sound, Bristol Bay, and along the Arctic Coast.

Very little is known regarding the depths of water, the character of the bottom, the behavior of tides and currents, or other geophysical characteristics of Arctic coastal waters. The survey of this coast has presented problems not heretofore encountered by our hydrographic parties. Among these are the problem of logistics and the application of methods consistent with the low temperature conditions found in this area. Ice conditions introduce many new problems for the hydrographer. What appears to be indicated is the development of a practical method of obtaining water depths by acoustic or electronic means through the surface ice.

The Coast and Geodetic Survey has continued the practice of running sounding lines across the Gulf of Alaska. This project was begun in 1925 and was continued every year without interruption until 1941. It was resumed in 1945. To date over 56,000 nautical miles of sounding lines have been run in this area with a total of more than 79,000 recorded echo soundings, well controlled in position. Much valuable information has thus been accumulated, of particular interest to the geophysicist, such for example as the numerous submarine mountains, the deep trenches, and the many depressions. Most of these have been reported on to this body or to other

interested societies. At the close of the 1947 field season, the ship Pathfinder while returning to the United States from its working grounds in the Aleutians, discovered a hitherto unknown but important seamount. This feature was found in the North Pacific Ocean about 800 mi northwest of Seattle in latitude 50°57'N, longitude 143°11' W. It rises to a height of nearly 9800 ft from surrounding depths of over 12,500 ft. A complete graphic profile record was obtained of the mountain. The least depth recorded was 460 fathoms (2760 ft). It is probable that when fully developed the mountain will reveal even shoaler depths.

This spring, the ship Explorer, on its most recent passage to the westward, developed a previously located submarine mountain and determined a least depth of 37 fathoms (222 ft). This seamount rises from depths of 1800 fathoms (10,800 ft) and lies 125 mi southwest from Dixon Entrance.

Under the Philippine Rehabilitation Program the survey work in the Islands, interrupted by the War, was resumed. Much of the previously collected data has either been damaged or lost. As a part of this program a number of Filipinos are being trained each year for eventual taking over of the survey work.

For the 1948 season hydrographic surveys are planned in the offshore areas of the eastern portion of the Gulf of Mexico to a distance of approximately 120 mi from the coastline to the general vicinity of the 100-fathom curve; an extension of hydrography in the central portion of the Aleutians; and extensive basic surveys in the Bristol Bay area and along the Arctic coast of Alaska.

The tidal activities of the Survey have been expanded considerably. The records obtained from tide stations over long periods of time are providing very important information regarding changes in sea level, in addition to furnishing information required for navigation and charting.

At the present time we have 96 tidal stations in operation. This network of stations covers most of the coastal places throughout the western hemisphere. Through further cooperative efforts the system will be extended.

Preparation of tidal bench mark index maps and revision of datum plane information for many of our coastal states has been completed during the year.

Special tidal investigations were made in the David Taylor Model Basin, at Carderock, Maryland. Analysis of observations over a seven-day period disclosed a minute tide, to the extent of 0.003 inch, in the basin, and of movement of the Earth due to the Earth tide and tidal loading near the coast. A report of this investigation is being prepared for publication in the Transactions by W. B. Zerbe, Chief, Section of Oceanography in the Division of Tides and Currents.

The comprehensive current survey of Puget Sound, Washington, which had been in progress during the winter season for a number of years, was completed early in 1947. From the results of this survey and other available data tidal current charts depicting the details of the current movement for each hour of the tidal cycle have been prepared. The Current Tables, Pacific Coast, have been improved by a general revision of the information for the southern part of Puget Sound and the inclusion of daily predictions for The Narrows.

A detailed current survey of Delaware Bay and River, from the Capes to Bordentown, New Jersey, was made during the summer of 1947. Data from this survey are now being used to prepare hourly tidal current charts.

The program of securing long series of hourly current observations at selected lightship stations along our coasts has been resumed in cooperation with the United States Coast Guard. Several offshore current stations are now in operation.

The Survey realizes the importance of adding to our knowledge of the currents in several important waterways. It is only lack of operating funds which have prevented comprehensive study of the currents in various Aleutian Island passes, and in the passages through the San Juan Archipelago in Washington.

To increase our fund of information on harbor and coastal waters, observations of the temperature and density of the surface water are obtained daily at most of the tide stations operated by the Bureau. Publications giving the results of these observations are revised every two years. A revised edition of the publication Surface Water Temperatures, Atlantic and Gulf Coasts was issued in 1947.

Progress has been made in connection with our seismic sea-wave studies. Three steps have thus far been taken towards establishing a seismic warning system: A chart has been published showing the time required for a seismic sea wave to reach Honolulu from an earthquake epicenter in the Pacific; a seismic sea-wave detector has been devised and is undergoing field tests; and a chronological file of seismic sea-wave data has been set up. Photostats of tide marigrams showing receipt of sea waves, related material, and a comprehensive listing of future wave receipts will be maintained in this file.

In the development and issue of nautical charts of our coastal waters, attention is invited to the treatment of Charts 1000 and 1001 covering our Atlantic seaboard for use with the Loran system of navigation. In the revision of the Survey's existing charts, surveys are being applied as rapidly as seasonal field results can be compiled and reviewed.

Our knowledge of the ocean floor is being constantly enlarged on. Thousands of sq mi of soundings, as well as collateral geophysical data, are being gathered by the field parties of the Coast and Geodetic Survey each year and made available for the construction of nautical charts and for scientific study in areas heretofore only meagerly surveyed or not surveyed at all. New techniques being developed in the field of hydrographic surveying will permit a more nearly accurate correlation of oceanographic data in the region of the Continental Shelf and beyond.

U. S. Coast and Geodetic Survey,
Washington, D. C.

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OCEANOGRAPHIC ACTIVITIES OF THE CORPS OF ENGINEERS

Martin A. Mason

The Corps of Engineers of the United States Army is not usually considered as being concerned with oceanography; however, as frequently occurs in this complex technical age, unlikely interests are often important. Generally speaking, the primary interest of the Corps of Engineers in oceanography is one of usage and application of results rather than research or development of new knowledge. Research is important in the oceanographic activity of the Corps of Engineers but it is of the nature of applied rather than basic research.

The three agencies of the Corps of Engineers most concerned with oceanography are the Beach Erosion Board, the United States Lake Survey, and the Waterways Experiment Station. None of these agencies is primarily concerned with oceanography but they perform much work of value to oceanographers.

The Beach Erosion Board is designated by statute as the Federal agency responsible for the research and investigation necessary to devise means of preventing erosion of the shores of the United States by waves and currents and to develop methods for the protection, restoration, and development of beaches. In the discharge of this duty the Beach Erosion Board has necessarily undertaken some oceanographic work, notably in the study of ocean-wave action, tide and current phenomena, and the littoral movement of material on the sea bed and beaches.

The Board is establishing four wave-measurement stations, at Long Branch, New Jersey; at the Standard Oil Company pier, El Segundo, California; at the pier at Huntington Beach, California; and in cooperation with the Humble Oil and Refining Company on an oil well drilling platform about seven mi offshore of Grand Isle, Louisiana, in the Gulf of Mexico. These are the first of a number of permanent wave-recording installations to be made on the Atlantic, Pacific, Gulf, and Great Lakes shore lines. The wave gages are of the step-resistance type, surface mounted on piers, piles, or other available structures. The waves recorded will be shallow-water waves, although at the Long Branch and El Segundo locations deep-water wave gages of the pressure type will be used also for at least a short time.

At Long Branch, the Board has established a new tide station in cooperation with the United States Coast and Geodetic Survey.

Studies of the movement of material in depths of water up to 60 ft are being made at Long Branch and at the two Southern California locations by means of repeated precise profiles, sand sampling, and current measurements. At the Long Branch location a 600,000-cu yd submarine stock pile of material is being created by the dumping of material dredged from the entrance channels to New York Harbor in an area about 200 yd by 1500 yd, with an average depth of about 38 ft. In the California areas two artificially built beaches, one created by the deposit of 1,092,000 cu yd of material adjacent to the Anaheim Bay entrance jetties, the other by a 14,000,000-cu yd deposit derived from the site of the new Los Angeles sewage treatment plant at Hyperion, are being studied to relate the movement of beach material to oceanographic conditions.

The Beach Erosion Board has constructed a model of a new wave tank in which waves six ft high and 300 ft long may be generated in water depths of 15 ft for the purpose of full size studies of wave action on structures, including revetment for earth dams, breakwaters, and other structures and for determining the wave run-up on sloping face structures. The full size wave tank is expected to be in operation in early 1949.

In the laboratory the Beach Erosion Board is conducting tests to determine the variables controlling the profile of beaches. An extension of this study involves the determination of the model law relationships and transferability of model beach test results to the prototype when sand movement on the shore is the principal phenomenon to be investigated.

The Beach Erosion Board is responsible for the coordination of research and development in the Corps of Engineers of methods for shallow water hydrographic surveying. The United States Lake Survey performs the service of surveying and charting, for navigation purposes, the Great Lakes and connecting streams. Charts and bulletins published at intervals supply full descriptions of physical conditions and particulars of changing conditions. The chief interest of oceanographers in the Lake Survey work probably lies in these publications; however, some work is done on seiche action in the Great Lakes as it affects the water levels in the lake system. Data on fluctuations of water level, storms, fog, and magnetic observations are available for the Lakes.

The Waterways Experiment Station is principally a testing agency concentrating on model testing of various waterway projects of the Corps of Engineers. In connection with some of its shorefront harbor or inlet improvement tests, data on oceanographic conditions at specific localities are obtained. Considerable work has been done in the study of wave forces on structures and in the determination of the effects of long waves in the ocean on harbors, as well as the study of surges in harbors.

Military interests of the Corps of Engineers have some oceanographic aspects, particularly in connection with methods of determining shallow water depths and the usage of beaches in time of war, that require the collection of data useful to the student of oceanography.

Engineering and Research Branch,
Beach Erosion Board,
Washington, D. C.

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DISCUSSION OF

"INVESTIGATION OF UNDERWATER PRESSURE RECORDS AND SIMULTANEOUS SEA SURFACE PATTERNS" by H. R. SEIWELL

[Trans., v. 28, pp. 722-724, 1947]

R. G. Folsom (University of California Fluid Mechanics Laboratory, Berkeley, California)--According to the paper prepared by Seiwell, a correction factor of about 1.35 must be applied to bottom pressure measurements of wave heights in order to obtain the correct wave-surface wave height when the theoretical equations for oscillatory flow are used in the calculations. Laboratory and field investigations by the University of California Fluid Mechanics Laboratory group have demonstrated this value to be about 1.1. The discrepancy in reported magnitudes is excessive and further investigations should be made to determine the reasons for the difference.

In addition to the University of California laboratory results, ten determinations of the correction factor in the wave tank at Vicksburg gave an average magnitude of 1.07. Field observations by the University of California made with the aid of floating spar buoys and recording pressure gages at the bottom of the spar in the open ocean, admittedly rough measurements, showed the correction factor for conditions near the surface to be about 1.15. Further measurements with ocean waves in shallow water at a depth of about 20 ft show correction factors in the order of 1.1.

Investigation of the theoretical curves contained on Figure 1 of Seiwell's paper indicates that the relationships correspond to deep-water conditions. The test values used for comparison were obtained in 75- and 120-ft depths over a range of periods such that shallow-water conditions existed at the larger periods. When the shallow-water characteristics are plotted, the discrepancies between experimental and theoretical relationships are reduced. If the calculated correction factor of 1.35 was based on the deep-water curves, the correction factor obtained is not correct and should be modified.

Another report on the same investigation by the same author, unpublished, contains photographs of the spar buoy used for determining the surface-wave profiles. These photographs show the longitudinal spar buoy to be at an appreciable angle with respect to the vertical. Theoretical and experimental work at the Fluid Mechanics Laboratory has demonstrated that an error in wave heights will be made when the water-line elevation on the spar buoy is such that tilting from the vertical occurs.

In oscillatory waves, horizontal velocities occur during a portion of the time. The spar buoy may have some horizontal motion. For example, if the spar when anchored in 75 ft of water were to move five ft horizontally from the vertical position during the passage of a wave, the change in absolute elevation of the spar buoy would be about 0.2 ft. The report does not include a consideration of errors introduced by possible drift.

Taking into consideration the sloping position of the spar buoy and errors introduced by small drift (the errors introduced are apparently compensating), it does not appear that the 0.05 ft probable error indicated by the author is correct. A recalculation of these field data in terms of items noted would prove profitable and do much to explain the differences now reported by various investigators.

H. R. Seiwell (Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, Author's closure)--The technical points raised by Folsom are clarified in the complete report of this research, now in process of publication as v. 10, no. 4, of Papers in Physical Oceanography and Meteorology.

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of April 24, 1948

The meeting was called to order at 09^h00^m in the Reading Room of the National Academy of Sciences, National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by President O. E. Meinzer.

Present--Twenty-eight persons were present, namely: L. H. Adams; K. Hilding Beij; Wilbur S. Burbank; Perry Byerly; Horace R. Byers; Ernst Cloos; Frank L. Culley; H. N. Eaton; Richard M. Field; Jno. A. Fleming; Richard H. Fleming; R. C. Gibbs; H. D. Harradon; Henry W. Hemple; M. King Hubbert; Earl Ingerson; H. Freeborn Johnston; David G. Knapp; Walter D. Lambert; Ray K. Linsley, Jr.; John Putnam Marble; A. G. McNish; Oscar E. Meinzer; Frank Neumann; Florence Robertson; Irvin Roman; Waldo E. Smith; and H. T. Stetson. The following were excused because of absence from the city or for other reasons: Robert Balk; J. Bjerknes; L. O. Colbert; Richard E. Fuller; Benjamin Holzman; J. B. Macelwane; Martin A. Mason; Geo. F. McEwen; G. Medina; J. S. Nicholas; F. W. Reichelderfer; Paul Sollenberger; V. C. Stechschulte; Lorenz G. Straub; W. D. Sutcliffe; Thomas G. Thompson; F. J. Viehmeyer; and Francis G. Wells.

Approval of Minutes--The minutes of the meeting of November 28, 1947, as published in the February 1948 issue of the Transactions, pages 142 to 149, were approved.

General Secretary's Report

Executive Committee--John S. Nicholas has been named Chairman of the Division of Biology and Agriculture of the National Research Council, succeeding Raymund L. Zwemer who has been acting chairman since the retirement of Robert F. Griggs, June 30, 1948, thus becoming a member of this Committee.

Financial Report--The financial report for the fiscal year ending June 30, 1948 will be prepared promptly at the close of the year, for submission to the Committee on Audit.

The cash balance on April 1, 1948 in all funds of the Union was $20,855.58 which included $16,908.87 for the general purposes of the Union, $142.30 for the William Bowie Medal Fund, and $3,804.41 for the special fund left to the Union by the late Robert E. Horton. In accordance with the instructions of the Executive Committee, October 25, 1946, five $500 Series F Government bonds were purchased at a cost of $1850. These are not included in the above total.

As reported in November an application was made to the Geological Society of America for a grant in the amount of $7500 for a period of three years beginning with the current calendar year. The Geological Society of America has approved the grant for the first year in the amount of $3000, the first half of which has been received. On April 16 the Honorary President, President, and General Secretary made a trip to New York to confer with the President, Treasurer, and Secretary of the Geological Society of America. It was mentioned that the Geological Society of America is taking steps to amend its statutes and by-laws to regularize the affiliation of other societies. Following the approval of this, it is the thought that possibly the American Geophysical Union could be one of the affiliated organizations. It was pointed out that no commitment has been made by the Geological Society of America to extend the grant beyond the current year, and that the grant had been made expressly for and in publishing the Transactions.

The work on the contract with the Joint Research and Development Board has been progressing steadily and we anticipate completing this contract in advance of June 20, 1948.

Membership--The rapid growth of membership which began just after the Annual Meeting in 1947 has continued due to the great efforts of Chairman Johnston and the members of his Committee. The following gives a summary since November 28, 1947:

Members, November 28, 1947	3743	
Inactive to active status	2	
New members	622	
Reinstated	1	4368

Resignations	69	
Deceased	8	
Dropped	1	78
Membership, April 16, 1948		4290

Eight deaths have been reported in the membership since November 28, 1947, namely: Luther C. Snider, May 24, 1947; Arthur A. Young, July 8, 1947; Benjamin A. Wooten, July 9, 1947; Frank L. Flynt, September 10, 1947; Kendall E. Born, September 21, 1947; Harold B. Ward, January 4, 1948; James M. Little, March 7, 1948; and Alfred C. Lane, April 15, 1948.

Ninety-eight members have not paid dues for two years ending December 31, 1947 and in accordance with the provisions in the By-Laws are hereby reported to the Executive Committee with the recommendation that they be dropped from the rolls of the Union, except that the General Secretary be instructed to make one more attempt to bring them back into active membership following which, at his discretion, those who do not respond are to be dropped. Last year a similar final effort resulted in nine responses from the 32 reported, who are now members in good standing.

Administration of the Union--The officers of the Union have made arrangements for the continued housing of the office of the Union for another year in the Administration Building of the Carnegie Institution of Washington.

National Research Council--The National Research Council has made provision in its budget for the next fiscal year for a grant of $400 for the work of the Union. This is the same amount that has been granted in recent previous years.

The American Geophysical Union has been called upon by the National Research Council to make recommendations of delegates to the Sixth International Congress of Photogrammetry to be held at The Hague, Netherlands, September 1 to 10, 1948. Two members, Prof. George H. Harding of the Ohio State University and Comdr. Oliver S. Reading of the United States Coast and Geodetic Survey have been recommended. It is understood that they will go without expense to the Union.

During recent months we have attempted to get the names of all those who plan to go as American delegates to the Eighth General Assembly of the International Union of Geodesy and Geophysics to be held in Oslo, Norway, August 19 to 28, 1948. Fifty-four names have been recommended to the National Research Council as delegates and in addition 20 have been listed as guests. Dr. Fleming will present further information on this matter. There has been no general plan for the financing of trips through UNESCO funds, under the Fulbright Act, or any other general source, and Transport Command planes will presumably be available for passage only for those who have a military connection.

Meetings--The Twenty-Second Regional Meeting was held in Berkeley, California, February 13 and 14, 1948, and sessions were held by the Sections of Meteorology, Oceanography, and Hydrology. One hundred and forty-nine registered but the total attendance was somewhat greater.

Publications--As reported in November 1948, we were at that time ordering 4500 copies of our Transactions to meet the rapidly growing membership requirements. Since January 1948, this number has been increased to 5200. The Transactions of December and February have been distributed to members and subscribers, and under the exchange arrangements, since our November meeting. The April issue has just been received from the printer and is being prepared for mailing.

Affiliation with the American Geological Institute--Under date of December 10, 1948 a letter was received from the Organizing Committee inviting the American Geophysical Union to affiliate with the American Geological Institute. A recommendation in this connection will be made later by the Chairman of this Committee. In this connection, however, a recent letter from President Straub of the Section of Hydrology should be noted suggesting that inasmuch as many matters of the AGU bear upon physics we should also investigate the possibilities and possible advantages of affiliation with the Institute of Physics.

Consideration of the field of sedimentation--At the meeting of the Executive Committee on November 28, 1947 the matter of the desirability of establishing a Section of Sedimentation was referred to the Section of Hydrology for study as there now exists a Committee on Sedimentation in that Section. A report will be presented later by a representative of the Section of Hydrology.

United States National Commission for UNESCO--A Pacific Regional Conference of the U. S. National Commission for UNESCO is to be held in San Francisco, California, May 13 to 15, 1948. The American Geophysical Union was requested to name delegates or representatives from

Arizona, California, Idaho, Montana, Nevada, Oregon, Washington, Hawaii, and Alaska. The following have indicated that it will be possible for them to attend this meeting without expense to the Union and have been named as our official delegates: California, Perry Byerly and Frank J. Veihmeyer; Washington, Richard E. Fuller, and Thomas G. Thompson; Oregon, J. C. Stevens; Nevada, Vincent P. Gianella; Hawaii, Chester K. Wentworth. We have requested that the delegation name its own chairman.

French Society of Civil Engineers--A representative of the French Society of Civil Engineers in this country has requested the American Geophysical Union to name delegates to their centennial celebration to be held in Paris May 28 to June 5, 1948. We have nominated Lorenz G. Straub and Walter C. Lowdermilk to be our delegates. Dr. Straub plans to present a paper entitled "Experimental Problems in Fluid Flow." These delegates will attend without expense to the Union.

Dedication of Exploration and Production Laboratory of the Shell Oil Co.--M. King Hubbert was designated as the representative of the American Geophysical Union at the dedication of the new laboratory on December 5, 1948.

Sesquicentennial Celebration of the founding of the University of Louisville--Lucien Beckner was designated as representative at the Sesquicentennial Celebration of the founding of the University of Louisville held on February 9 and 10, 1948. He reported that 225 colleges and universities were represented and that there were representatives from many scientific societies and from 12 foreign countries.

Action on General Secretary's Report--The report was approved, including the recommendations concerning members in arrears in dues.

Transfers within the budget--The General Secretary recommended the transfer of unexpended budgeted items to other accounts as follows: To Transactions, $150; to Stationery and Miscellaneous $200; to Committees, $1000. This was approved.

International Union of Geodesy and Geophysics--Jno. A. Fleming outlined the progress of IUGG and its parent organization, The International Council of Scientific Unions, and their relationships to UNESCO. He mentioned the grants that have been made by UNESCO for scientific purposes, and that these grants are not made on a continuing basis. A complication is involved in the fact that the adhering countries to UNESCO are not identical with the adhering countries to the various international unions. A special commission has been set up to handle the problems involved.

Reports of Standing Committees

Membership--Chairman Johnston reported on the continued activity of the Committee during the last few months, and presented the name of Finne Ronne, just returned from the Ronne Antarctic Research Expedition, for membership. He mentioned the splendid report given by Comdr. Ronne at the Special Evening Session on April 22, 1948 [see Transactions of June 1948, p. 429], and that friends of Comdr. Ronne and of the Union had made up a fund to pay for a life membership for him. A motion to elect him to membership for life was approved.

It was moved, seconded, and passed that the Executive Committee extend to the Committee and especially to Chairman Johnston, thanks for the outstanding work they are doing in bringing qualified persons into the membership of the Union.

Chairman Roman of the Sub-Committee on Corporation Membership reported briefly on the activity of this Sub-Committee.

Meetings--Chairman Marble presented a summary of his report presented before the Annual Meeting [see Transactions for June 1948, p. 433], pointing out the development of policy with regard to regionalization and regional meetings. The value of symposia and joint meetings with other groups was also mentioned.

Budget--Chairman Eaton presented the budget recommended by the Committee for the year ending June 30, 1949. This report with special recommendations as approved by the Executive Committee is presented in Appendix 1. This is in a form modified from previous years, segregating the operating statement from assets and liabilities. Especial attention is called to the first of the five recommendations relating to increase in dues. Under our Statutes and By-Laws our dues are fixed by the Executive Committee and are not to exceed $5 for each calendar year. The Executive Committee, in approving the first recommendation of the Committee on Budget, agreed that

the Committee should place the matter of increase in dues before the membership early in 1949, recommending modification of the By-Laws to permit an increase. The Committee on Statutes and By-Laws was requested to submit changes to implement this recommendation to the meeting of the Executive Committee in the fall of 1948.

Reports of Special Committees

Affiliation with the American Geological Institute--The report of the Committee (Appendix 2) was read, and after discussion, was approved with the specific provision that the American Geophysical Union become one of the adhering organizations of the American Geological Institute. Authority for the Executive Committee to make this decision was given at the time of the election in the spring of 1947 [see Transactions of June 1947, p. 497]. In accepting the report of the Committee, its valuable services were acknowledged and the Committee was discharged with thanks.

President Meinzer suggested that at the next Annual Meeting, the special research committees should be given regular places on the scientific program to give them encouragement and opportunity to present information on their progress.

Reports of Divisions of the National Research Council Represented on the Executive Committee of the American Geophysical Union

Division of Physical Sciences--Chairman Gibbs reported completion of plans to republish two volumes of the Physics of the Earth Series, namely, Terrestrial Magnetism and Electricity (Vol. VIII) and Hydrology (Vol. IX). It was approved that the volume on the Internal Constitution of the Earth (Vol. VII) should be revised before republication. He reported the appointment of an advisory committee on Geophysics to aid the Office of Naval Research [see Transactions, v.29, April 1948, p. 294] and the program of fellowship of the Atomic Energy Commission under the National Research Council [see Transactions, v. 29, April 1948, p. 302]. He expressed the thought that upon the establishment of the National Science Foundation, funds might be available for the expenses of delegates to international meetings.

Reports of Sections

Hydrology--Secretary Linsley reported the Best Paper Award of the Section to Vincent J. Schaefer for his paper, "Properties of Particles of Snow and the Electrical Effects They Produce in Storms" [see Transactions, v. 28, August 1947]; and the Best First Paper Award to William C. Spreen for his paper entitled "A Determination of the Effect of Topography upon Precipitation" [see Transactions, v. 28, April 1947].

Secretary Linsley also presented the report of the study made of the desirability of establishing a Section of Sedimentation (see Appendix 3). After discussion, the report, recommending no action at the present, was adopted. It was suggested, however, that a symposium on sedimentation might be desirable in drawing together those interested, and in developing unification in this field as suggested in the report.

New Business

M. King Hubbert raised a question concerning the contract with the Research and Development Board under which AGU is compiling a list of research workers in various of the fields of the geophysical sciences. It was pointed out that this contract was entered into in June 1947 by the officers of AGU to provide much needed information for this important Board, and was reported on at the meeting of the Executive Committee [see Transactions, v. 28, February 1947, p. 143].

R. M. Field, Chairman of the Commission on Continental and Oceanic Structure, IUGG, and Chairman of the Committee on the Social Value of the Earth Sciences, reported briefly on the work of this Commission and this Committee, noting that a full report would be given at the Eighth General Assembly of the International Union of Geodesy and Geophysics in Oslo, Norway, in August, 1948.

M. King Hubbert raised a question on the methods used by the Committee on Membership in securing new members, especially with regard to pre-sponsorship of individuals not personally known by the sponsors, and made a motion that personal acquaintance must be the basis for sponsorship. There was no second. It was explained that the names of those invited to apply in sending pre-sponsored blanks are carefully scrutinized by the Committee on Membership to be certain of their scientific qualifications and that pre-sponsorship offers no hazard, but overcomes

one of the awkward hurdles with which an applicant is often faced, namely, the determination of those of his acquaintance who are members. A motion was made, seconded, and passed that the Executive Committee express its complete confidence in the work of the Committee on Membership in this respect. In the ensuing discussion, relating to the grant of the Geological Society of America, it was reiterated that this grant is entirely for the purpose of aiding in the cost of publication of the Transactions, and that regular Union funds are available for carrying on the work of the Committee on Membership. A motion was made and passed that this grant be used exclusively to aid in publication of the Transactions.

Adjournment--The meeting was adjourned at 13^h06^m.

K. HILDING BEIJ, General Secretary
WALDO E. SMITH, Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON BUDGET FOR THE FISCAL YEAR ENDING JUNE 30, 1949

H. N. Eaton, Chairman
Jno. A. Fleming Roy W. Goranson N. C. Grover

The Committee on Budget of the American Geophysical Union has conferred with the General and the Executive Secretaries of the Union regarding the budget for the fiscal year, July 1, 1948 to June 30, 1949, and proposes the following budget. Note that the form of the statement has been changed this year for the sake of clarity, the Operating Statement of estimated receipts and expenditures being separated from the Statement of Assets and Liabilities.

A change in the designation of certain funds should be noted. After consultation with the officers of the Union, the Budget Committee has set up in the budget a Permanent Fund comprising four life memberships at $100 each and the sum of $1850, representing the cost value of U. S. Government bonds purchased earlier as an investment. The main purpose of the Permanent Fund is to separate from the operating funds special funds which are not available for general expenditures, such as payments for life memberships. It will provide a means for handling future special funds, such as that anticipated from the Horton estate.

In the present budget, the fund previously called a Cash Bank Balance is called a Reserve. This name seems appropriate, since the Reserve includes the cash available for general expenditures and affords a means of meeting deficits and of absorbing surplusses.

Statement of Assets and liabilities as of June 30, 1948 (estimated)

Assets		
Cash:		
Reserve	$12,700.00	
Permanent Fund	2,250.00	
Robert E. Horton Fund	3,600.00	
William Bowie Medal Fund	133.00	$18,683.00
Bills receivable		2,925.00
		$21,608.00
Liabilities		
Bills payable		$ 1,600.00
Surplus (capital account)		20,008.00
		$21,608.00
Operating statement		
Estimated receipts		
Grants:		
National Research Council	$ 400.00	
Geological Society of America	1,500.00	$ 1,900.00
Anticipated income:		
Dues, 4500 members	$22,500.00	
Sales, Transactions	3,000.00	
Sales, reprints	2,000.00	$27,500.00
To be drawn from William Bowie Medal Fund		20.00
To be drawn from reserve		6,700.00
		$36,120.00

Estimated expenditures		
Publishing Transactions:		
Printing	$8,000.00	
Preparing manuscript	2,400.00	
Time of Executive Secretary	2,900.00	
Envelopes, cost and preparation for mailing	400.00	
Postage	300.00	$14,000.00
Reprints:		2,000.00
General expenses, Office of Union:		
Services, Executive Secretary	$4,100.00	
Services, stenographic and clerical	8,200.00	
Stationery and miscellaneous	1.100.00	
Postage and communications	900.00	
Office equipment	600.00	$14,900.00
Expenses, meetings:		
Annual Meeting	$ 500.00	
Regional Meetings	300.00	$ 800.00
Expenses, Sections		200.00
Expenses, Committees		1,250.00
List of Members and Officers		1,200.00
Honoraria to co-editors		1,500.00
Travel of officers		250.00
William Bowie Medal		20.00
		$36,120.00

Statement of assets and liabilities as of June 30, 1949 (estimated)

Assets		
Cash:		
Reserve	$6,000.00	
Permanent Fund	2,250.00	
Robert E. Horton Fund	3,600.00	
William Bowie Medal Fund	113.00	$11,963.00
Bills receivable (estimated)		3,000.00
		$14,963.00
Liabilities		
Bills payable (estimated)		$ 1,600.00
Reserve (capital account)		13,363.00
		$14,963.00

The Budget Committee makes the following recommendations:

(1) That, commencing January 1, 1950, the annual dues be increased to $7.00; that to this end the Committee on Statutes and By-Laws be instructed to prepare the necessary changes in the Statutes and By-Laws; and that these amendments be submitted to the membership, with the necessary explanations, for approval. The Committee has made a careful study of the present expense of operating the Union and has attempted to predict the effect on income and expenditures of increased membership. The cost per member has been in excess of $5.00 regularly, and there is no indication that this figure will be lowered appreciably by any probable increase in membership.

(2) That persons joining the Union during the first half of the fiscal year be charged dues for and receive Transactions for that year; and that persons joining the Union during the second half of the fiscal year pay dues for and receive the Transactions for that half of the year.

(3) That it is not advisable at this time to change the Statutes and By-Laws of the Union to provide for an entrance fee, provided the recommended increase in dues is approved.

(4) That provision be made for increases in the salaries of the Executive Secretary and for the stenographic and clerical staff in the Office of the Union. Specifically, the Committee recommends that the salary of the Executive Secretary be increased to $7,000 per annum and the salary of Samuel Pepper, secretary-stenographer, to $3,000, and that approval be given to increasing the salaries of three clerks to $2,400 each or to any intermediate salary deemed advisable if and when this may become necessary. Allowance has been made for such action in the budget.

(5) That an effort be made to find some means of paying at least part of the expenses incurred by officers of the Union who attend the Oslo meeting.

APPENDIX 2--REPORT OF SPECIAL COMMITTEE ON AFFILIATION WITH THE AMERICAN GEOLOGICAL INSTITUTE

W. T. Thom, Jr., Chairman

Ernst Cloos O. E. Meinzer (ex officio) F. W. Reichelderfer

In the Articles of Organization of the American Geological Institute, the American Geophysical Union is one of the 11 non-profit organizations listed as eligible for initial membership, and it is the recommendation of your Special Committee that the American Geophysical Union accept the invitation to become a Member Organization of this Institute.

As originally proposed the Institute was expected to be an over-all geoscientific organization quite independent of both the American Association for the Advancement of Science and the National Research Council. This plan has since been reversed and subject (1) to further approval by the National Academy of Sciences, and (2) ratification by seven of the eligible organizations, the Institute as now projected will be developed within the National Research Council, with the Council having two ex officio Directors in the Institute, and one appointed Director.

The purpose of the new organization is to be "the advancement of geology and its application to human welfare."

The Institute is to have the power to solicit and receive funds.

The Institute's Member Organizations are not to be subject to assessment for any purpose, and any Member Organization may resign by giving proper written notice to the President of the Institute.

It is the belief of your Committee that the American Geophysical Union, by adherence to the American Geological Institute, will demonstrate the Union's interest in fostering inter-society cooperation; may help to obtain funds for projects of geoscientific importance; will be under no financial liability by reason of such adherence; and can withdraw on short notice and at any time.

For these reasons, therefore, your Special Committee recommends that the American Geophysical Union ratify the Articles of Organization of the American Geological Institute, as drafted on December 10, 1947, and become a Member Organization within the Institute.

APPENDIX 3--A REPORT TO THE EXECUTIVE COMMITTEE OF THE AMERICAN GEOPHYSICAL UNION ON A PROPOSED SECTION ON SEDIMENTATION

At the Executive Committee Meeting on November 28, 1947, a recommendation for the establishment of a Section on Sedimentation was referred to the Section of Hydrology for study. The Executive Committee of that Section discussed this proposal at some length. It is interesting to note that subsequent to the referral of the original proposal, a letter from Allen C. Tester of Iowa State University was received making a similar recommendation.

It was the opinion of the Executive Committee of the Section of Hydrology that the interest in sedimentation is not sufficiently unified to warrant the establishment at this time of a new section which would cut across the fields of interest of established sections. It was felt, however, that there might be a need for closer coordination between existing sections with interest in the field of sedimentation. Accordingly, the president of each section was contacted for an expression of opinion as to the advisability of establishing a special Committee for this purpose. To date replies have been received from six of the seven other sections. Three of the six replies favored the establishment of such a committee, but none of the sections indicated a desire to be represented on it.

Accordingly, the Executive Committee of the Section of Hydrology recommends that no action be taken on the proposal. In lieu thereof, it is suggested that those sections having interests in the field of sedimentation contact the appropriate Research Committees of the Section of Hydrology for purposes of coordination. At some later date when interest in the field is more unified, the matter can be reviewed again. At the present time, the Section of Hydrology has the following research

committees which consider phases of the sedimentation problem: Committee on Lakes; Committee on Dynamics of Streams; and Committee on Land Erosion.

RAY K. LINSLEY, JR.,
Secretary, Section of Hydrology

REPORT OF THE AMERICAN GEOPHYSICAL UNION REPRESENTATIVES TO THE PACIFIC REGIONAL CONFERENCE ON UNESCO

Perry Byerly, Chairman

Richard E. Fuller — J. C. Stevens
Vincent P. Gianella — Chester K. Wentwort

The Committee, appointed to represent the American Geophysical Union at the Pacific Regional Conference on UNESCO, San Francisco, May 13, 14, and 15, 1948, reports as follows:

All the members attended the meetings. After a morning of registration, the meetings were opened by a general luncheon of all the delegates at the Palace Hotel. During the luncheon the delegates were addressed by Mrs. Louise Wright of Chicago and Lynn T. White, Jr., President of Mills College.

The afternoon was occupied by a general meeting in the Opera House. After a welcome by Elmer E. Robinson, the Mayor of San Francisco, the delegates heard two powerful addresses by Assistant Secretary of State George V. Allen and Dr. William Carr of the National Education Association. The speakers were forceful and the seriousness of the duties of UNESCO and the need for vast effort, and that quickly, was impressed upon the members. An account of UNESCO's past accomplishments and hopes for the future was presented. The efforts to make contact with the Soviets have not proved very successful. The need for such contact was emphasized. The members felt inspired and yet grave after these addresses.

The delegates then broke up into sections, of which there were five: (1) Communication, (2) Education, (3) Cultural Interchange, (4) Human and Social Relations, (5) Natural Science. Most of our members attended the Section of Natural Science, but reports of all sections were later distributed to all members.

Since the immediate duty of UNESCO is to prevent war, there was of necessity a certain similarity of approach in all sections. The Natural Science section discussed mainly the social implications of natural science. There was a strong feeling that local groups must discuss the problems of world betterment, that salvation lies in spreading throughout the world an interest in the betterment of the whole world. Our duty lies first at home. We were assured that UNESCO had already bent every effort at its command to broadening the channels of communication abroad. The importance of unfettered teachers in widening the outlook of our children was emphasized. Racial and religious tolerance was discussed in several sections. The appreciation of different cultural standards in different parts of the world was stressed and the advantages of student exchanges. The need of population control was agreed upon by Section (5). Much of the discussion in that Section centered on conservation of natural resources. We learned that machinery for the distribution of knowledge of agricultural techniques is highly developed already, but that economic inability to use such techniques prevents their spread. Atomic warfare came in for its share as the discussion turned toward moral responsibility of scientists. Section (5) recommended efforts toward strengthening the United Nations.

Two plenary sessions closed the meetings. The delegates felt that UNESCO has a vital part to play, but felt perhaps a vagueness as to how they can do something quickly to help keep the peace.

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NOTES AND PERSONALIA

NOTES

Seventh Pacific Science Congress--As announced earlier, the Seventh Pacific Science Congress is to be held in Auckland and Christchurch, New Zealand, February 2 to 23, 1949. Persons interested should write to Dr. Gilbert Archey, Secretary General of the Congress, Auckland Institute and Museum, Box 27, Newmarket, Auckland, S. E. 1, New Zealand, sending a copy to Mr. Harold J. Coolidge, Executive Secretary, Pacific Science Board, National Research Council, Washington 25, D. C.

Second International Conference on Soil Mechanics and Foundation Engineering--This Conference was held in Rotterdam, The Netherlands, June 21 to 30, 1948. On the United States Delegation were the following AGU members: T. A. Middlebrooks, Chairman; Gail A. Hathaway, and Carl P. Vetter.

Earthquakes, February to May 1947--The United States Coast and Geodetic Survey, cooperating with Science Service, the Jesuit Seismological Association, and a selected group of widely scattered seismograph stations, has located provisional epicenters during this period as shown in Table 1.

Table 1--Provisional epicenters of the United States Coast and Geodetic Survey

Date	Time U. T.	Epicenter Lat.	Epicenter Long.	Approx. depth	Approx. mag.[a]	Remarks
1948	h m	°	°	km		
Feb. 6	1 33.6	18 N	146 E	200	....	Marianna Islands region
Feb. 9	12 58.4	37 N	26 E	...	7 1/4	Aegean Sea
Feb. 11	15 41.9	64 N	147 W	...	....	Central Alaska
Feb. 14	10 52.7	27.5 S	63 W	600	6 1/2	Santiago del Esteo, Argentina
Feb. 14	22 00.5	9 S	78 W	...	....	Western Peru
Feb. 14	22 02.2	64 N	147 W	...	....	Central Alaska
Feb. 18	20 29.8	82 N	43 E	...	6 3/4	Arctic Region
Feb. 28	2 58.1	53.5 N	133 W	...	6 1/2	Queen Charlotte Islands region
Mar. 1	1 12.7	3 S	130.5 E	...	....	Off west coast of New Guinea
Mar. 3	9 09.9	18 N	119 E	...	6 3/4	Off north west coast of Luzon, P. I.
Mar. 4	1 53.1	10 S	75 W	...	....	Central Peru
Mar. 7	18 50.2	54 N	161 E	...	....	Off east coast of Kamchatka
Mar. 8	16 07.9	6 S	157 E	...	....	Solomon Islands region
Mar. 9	18 48.0	3 S	147 E	...	6 1/2	Off northeast coast of New Guinea
Mar. 10	11 25.3	29 S	177 E	...	6 1/4	Kermader Islands region
Mar. 13	20 02.5	1 N	126 E	...	6 3/4	Molucca Passage
Mar. 14	21 56.7	17 S	75 W	...	6 3/4	Off southwest coast of Peru
Mar. 15	11 24.1	40 N	140 E	...	....	Off northern Honshu Island, Japan
Mar. 17	19 41.6	16 N	146 E	...	....	Mariana Islands region
Mar. 21	21 34.6	59 S	27 W	...	....	Sandwich Islands region
Mar. 22	0 06.3	14 S	75 W	100	....	Southwest coast of Peru
Mar. 22	21 34.5 23 41.2	11.5 N	86.5 W	...	....	Near coast of Nicaragua
Mar. 23	18 11.6	51 N	155 E	200	....	Off southern coast of Kamchatka
Mar. 24	5 19.5	6 S	104 E	...	....	Off southern coast of Sumatra
Apr. 12	6 15.3	14 N	90.5 W	200	....	Near coast of Guatemala
Apr. 17	16 11.5	33 N	135.5 E	...	....	Felt widely in southern Japan, Small seismic sea wave reported
Apr. 18	12 19.8	3 S	137 E	...	....	Northern New Guinea
Apr. 20	11 11.0	14 N	92 W	...	....	Off coast of Guatemala
Apr. 21	20 22.0	19 N	69.5 W	...	7 1/4	Near NE coast of Dominican Republic
Apr. 21	20 59.2			...		
Apr. 22	00 28.3	Aftershocks of				
Apr. 22	13 09.0	shock above				
Apr. 23	11 50.3					
Apr. 26	9 32.4	51 N	34 W	...	....	North Atlantic
Apr. 28	12 01.8	11 N	63 W	100	....	Off coast of Venezuela
May 8	2 46.5	46.5 N	151 E	...	....	Kurile Islands
May 9	2 08.8	30 N	129 E	...	6 3/4-7	Off southern coast of Kyushu, Japan
May 11	8 55.7	17 S	71 W	...	7 1/4-7 1/2	Casualties and damage at Arica, Moquegua, and Tacna, Peru
May 12	0 56.9	38 N	142.5 E	...	6 3/4	Off northeast coast of Honshu, Japan
May 14	22 31.7	54.5 N	161 W	...	....	South of Alaska Peninsula
May 17	17 48.6	55 N	161 W	...	....	South of Alaska Peninsula
May 23	4 12.5	18 S	169 E	200	6	New Hebrides Islands region
May 25	7 11.3	30 N	99.5 E	...	7 1/4	Sikang Province, China
May 25	15 13.2	43.5 N	127 W	...	5 1/2-6	Off coast of Oregon
May 26	9 16.7	56 N	156 W	...	6	South of Alaska Peninsula

[a]Magnitudes reported by the Seismological Laboratory, Pasadena, California.

Conference on Geophysics at the University of California--A two-day geophysical conference was held at the University of California in Berkeley, California, May 14 and 15, 1948. The program included sessions on meteorology, oceanography, and Earth physics with an evening meeting on the distribution of mountain building in geologic time in which the main paper was presented by James Gilluly. Other speakers included representatives from other California educational institutions, and R. Stoneley of Cambridge University, and E. C. Bullard of the University of Toronto.

Exchange of publications sought by Polytechnic Institute of Jassy, Romania--A communication from the Mathematical Department of the Polytechnic Institute of Jassy states that the library of the Institute was destroyed during the War, and that they desire to enter into exchange arrangements with American organizations. They also request original manuscripts in the various sciences for publication in their Bulletin. Communicate with Prof. Dr. D. I. Mangeron, Director of the Central Library and of the Mathematical Department, Polytechnic Institute, Jassy, Romania.

International Association for Hydraulic Structures Research--This Association held a meeting in Stockholm, Sweden, June 7 to 9, 1948. The newly elected officers are: President, Lorenz G. Straub (USA); First Vice President, E. Meyer-Peter (Switzerland); Second Vice President, A. N. Khosla (India); and Secretary, J. Th. Thijsse (Netherlands). In addition to the officers, the Permanent Committee includes G. Marchi (Italy); P. Danel (France); and Claude Inglis (England). Corresponding Members are B. Hellström (Sweden), and M. Bayer (Czechoslavakia). Wolmar Fellenius, retiring president, was elected Honorary Member and ex officio member of the Permanent Committee.

The Association will meet in Grenoble, France, in August 1949. Its next triennium conference will be held in Delhi, India in February 1951.

New map on status of aerial photography of the United States--The United States Geological Survey has recently issued the third edition of the index map showing aerial photography of the United States, corrected to March 15, 1948. Copies of the index map, giving instructions for procurement of prints, may be secured from the Map Information Office, United States Geological Survey, Washington 25, D. C.

PERSONALIA

George Baker, formerly a member of the staff of the Department of Geology, Melbourne University, Australia, is now Research Officer with the Council for Scientific and Industrial Research, Commonwealth of Australia. His headquarters remain in the Department of Geology of Melbourne University.

Beno Gutenberg of the Seismological Laboratory, California Institute of Technology, has been presented with a diploma of membership in the Finnish Academy of Letters and Science.

Lewis A. Jones of the Soil Conservation Service was recently given the Superior Service Award for his especially meritorious service through his leadership in the drainage and reclamation of swamp lands, and the conservation, use, and management of water resources.

Theodore A. Link has resigned as Chief Geologist of Imperial Oil Limited, and is establishing offices in Toronto and Calgary as a consultant.

Donald H. Menzel of Harvard College Observatory was recently elected to the National Academy of Sciences for his outstanding work in astronomy.

Hans Neuberger, Chief of the Division of Meteorology, the Pennsylvania State College, was promoted to the rank of Professor of Meteorology.

Ralph L. Parshall of the Soil Conservation Service was recently given the Superior Service Award of the United States Department of Agriculture for his development of water measuring and desilting devices in wide use throughout the world.

William A. Riggs, geologist and civil engineer of Shreveport, Louisiana, has been appointed as a member of the Industrial Relations Department of the Gulf, Mobile and Ohio Railroad, to make a systematic appraisal of the natural resources and physical assets of the territory served by the Railroad.

F. Dienert, Professor of the Institute National Agronomique, Rue de Seine 6, Paris 6, France, and Secretary of the International Association of Scientific Hydrology, IUGG, died April 7, 1948. Both President Lütschg and the Secretary have now died within a year. Gustaf Slettenmark of Sweden is carrying on as Acting President and A. Vibert of France as Acting Secretary.

James Macfarlane Little died at his home in Berkeley, California on March 7, 1948. He was born at Towanda, Pennsylvania on January 4, 1885. He received his baccalaureate degree in

mining and geology from Columbia University in 1907, and devoted the early years of his professional career to mining problems in the Southwest, Chile, and Australia. In World War I, he was a lieutenant in the Army Engineers Corps. Following this he resumed mine lease problems and research work with the Department of Public Service, Newark, New Jersey, and subsequently worked for several years on hydrologic work for the Soil Conservation Service. In 1939 he returned to the Southwest and devoted the rest of his life to mining problems in California. At the time of his death, he was with the California Division of Mines.

François Emile Matthes died at his home at El Cerrito, California on June 21, 1948, about two months after he was stricken with a severe heart attack. He was born in Amsterdam, Holland, March 16, 1874, and came with his family to the United States in 1891. He received his baccalaureate degree from Massachusettes Institute of Technology in 1896. He was awarded an honorary LL. D. degree by the University of California in 1947. He entered the United States Geological Survey in 1896, and retired after 51 years of distinguished service in 1947. He received a gold medal from the Department of the Interior only a few weeks before his death.

His outstanding work on topographic and geologic delineation is exceeded only by his work on glaciers on which he was a world-wide authority. He was the author of many important works: The Glacial Sculpture of the Big Horn Mountains; The Geologic History of the Yosemite Valley; The Chapters on Glaciers in the Physics of the Earth Series, Volume IX; The Glacial Anticyclone Theory Examined in the Light of Recent Meteorological Data from Greenland--Part I (it is hoped that the second and closing part may yet be published).

He worked actively in various scientific societies and was a past officer in a number. At the time of his death, he was Chairman of the Committee on Glaciers of the Section of Hydrology, AGU, and Secretary of the Commission on Snow and Glaciers of the International Association of Scientific Hydrology, IUGG, and had been working hard, in connection with the latter on reports relating to the Eighth General Assembly in Oslo in August 1948. He was active in Boy Scout work and twice was selected to lead a group of scouts on a complementary tour of the West. In 1931, he was awarded the Silver Beaver for his work with the scouts.

Donald G. McKeever of the Weyerhaeuser Timber Company, Tacoma, Washington, was killed by a falling snag February 5, 1948. He was born in Wilkinsburg, Pennsylvania, October 2, 1913, and received his baccalaureate degree in forestry from the University of Idaho. In 1936 he received his master of science degree from the same school. Since that time, he was engaged in forest research, and in 1942 became Director of Forest Research for the Weyerhaeuser Timber Company which position he occupied at the time of his death.

Oscar Edward Meinzer, President of the American Geophysical Union, died suddenly on June 14, 1948. An obituary appears on the opening pages of this issue.

Harold Murray, oceanographer and cartographer for the United States Coast and Geodetic Survey, died June 15, 1948 at his home in Washington, D. C. He was born at East Avon, New York, October 6, 1906. He was a graduate of Buchnell University and took graduate work in geology and science at George Washington University. He worked with the United States Coast and Geodetic Survey throughout his entire professional career.

SPECIAL ANNOUNCMENTS

Walter H. Bucher designated as President of AGU--Walter H. Bucher of Columbia University has been designated by the Executive Committee of AGU to be President of AGU to fill the unexpired term of the late Oscar E. Meinzer. This is in accordance with Article 5 of the Statutes.

American Standards Association--Fred Anderegg, AGU representative on the Committee on Photography Z38, of the American Standards Association advises that the latest standards approved by the ASA are as follows: Z38.1.43-1947, American Standard Dimensions of Inch-Size Photographic Papers. This is a revision of Z38.1.43-1944. Z38.7.8-1947, American Standard Practice for Microfilms. This standard defines the terms Microfilm, Microphotographs and Reduction; describes the material and the method of winding, the Format and Placement, Leader and Trailer, Title Frame and Reels. Z38.4.13-1948, American Standard for Distance Scales in Meters for Focusing Camera Lenses. This is a revision of Z38.4.13-1944. Z38.4.19-1948, American Standard Nomenclature for Parts of a Photographic Objective Lens. This standard defines the terms optical system, member, component, element, front, and back as applied to a photographic objective lens. Z38.4.20-1948, American Standard Method of Designating and Measuring Apertures and Related Quantities Pertaining to Photographic Lenses. This standard defines the clear aperture, entrance pupil, aperture ratio, relative aperture, and f-number; and gives methods for their measurement.

TRANSACTIONS
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ATMOSPHERIC SURFACE PRESSURE RELATED TO COAL MINE EXPLOSIONS

Charles L. Hosler

Abstract--Investigations into the synoptic situations preceding explosions in coal mines during the past 12 years show the feasibility of forecasting periods of dangerous accumulation of combustible gas mixtures in coal mines. Several physical, as well as some psychological, aspects are discussed.

Introduction--It is a well established fact that in certain coal mines, sudden falls in barometric pressure are accompanied by an increase in the amount of gas present. However, pertinent literature contains statements to the effect that mine ventilation completely eliminates this potential hazard [BEARD, 1908]. The purpose of this investigation is to determine whether such is the case in practice, or whether mine explosions that have occurred in the past are preceded or associated with characteristic weather situations and barometric tendencies.

General considerations--Explosive gas is held in spaces between layers of coal as well as between coal and bordering rocks. It may be contained in small pockets or in large reservoirs that have been created along faults or fissures. If the gases escape slowly at a more or less constant rate, their sources are called "feeders." If the gas comes forth with great velocity and force, its source is called a "blower" [BEARD, 1920]. Gases are also being produced constantly by chemical changes within the coal itself. These latter gases may be occluded in the coal under pressures of from 500 to 2500 lb/in^2, and generally transpire into the mine in small amounts. This is the usual condition. When the coal is broken into pieces during mining operations, the gases escape at a greater rate. Blowers and feeders consist largely of methane. The occluded gases along with some gases formed by acid water reacting with carbonates, account for varying amounts of methane, nitrogen, hydrogen sulfide, ethane, carbon monoxide, and carbon dioxide.

Methane in pure air constitutes an explosive mixture when in amounts varying from 7.14 per cent to 16.67 per cent by volume [BEARD, 1920]. These limits are lowered by the presence of other gases of good heat conductivity, and raised by those of poor heat-conducting qualities. Also, the explosive limits are extended by increased atmospheric pressure, owing to the increased density of the gas.

Considering the range of the explosive mixture, there can be too much explosive gas present as well as too little to create an explosion in the presence of an igniting source. Thus, when a copious gas source is opened, the dangerous range may be passed through twice, namely, while the percentage of gas is increasing above the lower limit, and while it is decreasing through the upper limit. A change in pressure at a time when the per cent of gas is close to either end of the explosive range might raise or lower the limits sufficiently to permit an explosion if an igniting agent is introduced.

Inasmuch as the flow of gases into the atmosphere of a mine is caused by a pressure differential existing between the place of confinement and the outside atmosphere, it seems logical to assume that the rate of flow is governed by the magnitude of the pressure gradient [HARGER, 1913]. That even small pressure changes may cause increased flow is illustrated by observations made by men working in wells without the aid of artificial ventilation; there, occasions have been reported where the air was good in the morning, but when the men returned in the afternoon they found too much gas present to allow work to be continued [MOSS, 1927]. The time factor in these observations corresponds well to the diurnal pressure fluctuations which have a maximum at 10^h00^m and a minimum at 16^h00^m local time. At the average latitude of the United States, the amplitude of the diurnal pressure fluctuation has a maximum of about 2 mb (0.06 in Hg) which is a small amount compared to that occasioned by the passage of a cyclonic storm which may cause a drop of 20 to 30 mb (0.6 to 0.9 in Hg).

Not only are pressure fluctuations effective in increasing the rate of flow of gas from already opened avenues of escape, but they are also capable of providing the trigger force for the opening of new pockets of gas. Such an opening may be concurrent with the violent shattering of a coal surface or the cave-in of a wall or roof. The magnitude of the trigger force is perhaps better

understood when we consider that the drop in pressure caused by the passage of a cyclonic storm reduces the atmospheric support of surfaces in mines from 40 to 70 pounds per square foot [BEARD, 1908]. This is an ample amount to allow a weakened roof to collapse. The debris piled up on the mine floor is apt to block effectively the passage of air and thus permit a dangerous accumulation of gas for lack of adequate ventilation. Also it may be pointed out that, concurrent with this effect on the ventilation, the roof falls may be accompanied by additional release of occluded explosive gases. Moreover, electric cables may be severed by such falls, and the ensuing short circuit then provides the ignition source.

The efficiency of a mine ventilation system is also decreased during lowering barometric pressure. The lesser density causes a lesser mass of air to be forced through the mine. This decreased ventilation efficiency occurs at a time when increased gas accumulation is likely to demand greater ventilation.

Another phenomenon directly related to pressure changes is the gob fire [HARGER, 1913]. Piles of coal waste are heated from within by chemical changes. The heat produced is sometimes sufficient to produce ignition if oxygen is present. Oxygen cannot reach the center of the pile where the heat is greatest unless the pile is disturbed in some manner. Rapid fluctuations in pressure allow the pile to "breathe" by forcing the air in and out. In this manner oxygen may reach the center of the pile in sufficient quantities to start a fire. It was believed for many years that wet coal burned better than dry coal because the fires were of greater frequency in wet weather. Later investigations proved, however, that the pressure fluctuations accompanying wet weather were the true cause [HALDANE and FOSTER, 1905]. If such a fire broke out in the presence of a combustible gas mixture, an explosion would result.

Scope of this study--In order to determine whether pressure changes do lead to conditions favoring an explosion, pressure data concurrent with a number of mine explosions were analysed. The period since 1936 was chosen in order to limit the considerations to present day mining practices and to facilitate the gathering of pertinent data.

The locations of all major mine disasters (explosions in which five or more persons were killed) since 1936 as listed by the UNITED STATES BUREAU OF MINES [1941] were marked on a map and the location of the nearest Weather Bureau station determined. The distance of the station from the explosion site did not exceed 50 miles in any of the cases considered. The record of pressures was then obtained from these stations for a seven-day period starting three days before the day of the explosion and continuing until three days afterwards.

The day of the explosion was designated as D-day and the days previous as D-1, D-2, and D-3 in order of their time distance from the explosions day. Analogously, the days following D-day were called D+1, D+2, and D+3.

Data were obtained for 41 explosions scattered over a 12-year period, from all regions of the United States where coal is mined. These data were then plotted with pressure as the ordinate and time as the abscissa (see Figs. 1, 2, and 3). The 41 curves thus obtained are pictures of the pressure fluctuations that occurred before, during, and after the mine explosions.

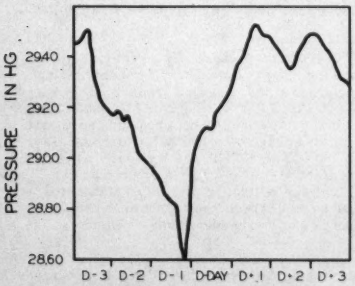

Fig. 1--Pressure curve for Centralia, Illinois, March 25, 1947 = D-day

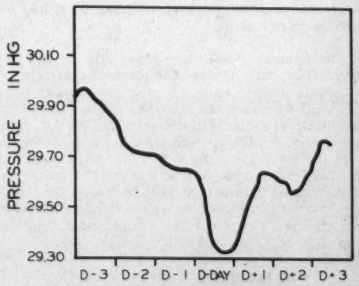

Fig. 2--Pressure curve for Pittsburgh, Pennsylvania, January 12, 1938 = D-day

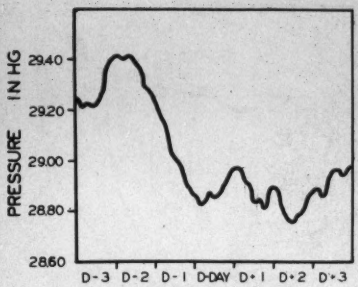

Fig. 3--Pressure curve for Terre Haute, Indiana, April 30, 1947 = D-day

Results--As an example, the mine catastrophe of Centralia, Illinois may be cited, where an explosion occurred on March 25, 1947 with a loss of 111 lives. Figure 1 shows the pressure trace from March 22 through March 28. Surface pressure patterns and frontal systems for 01^h30^m on March 23 and again on March 25 are reproduced in the weather maps of Figures 4 and 5. The weak frontal system with little associated weather change moved into the area on March 22 and 23, and on the morning of the 23 appeared as in Figure 4. By the morning of March 25 this system had developed into a deep cyclonic storm covering a considerable area, and had moved off to the northeast as shown in Figure 5. On this map past positions of the center for six-hourly periods are indicated by crosses. The location of Centralia, Illinois is shown by the circle.

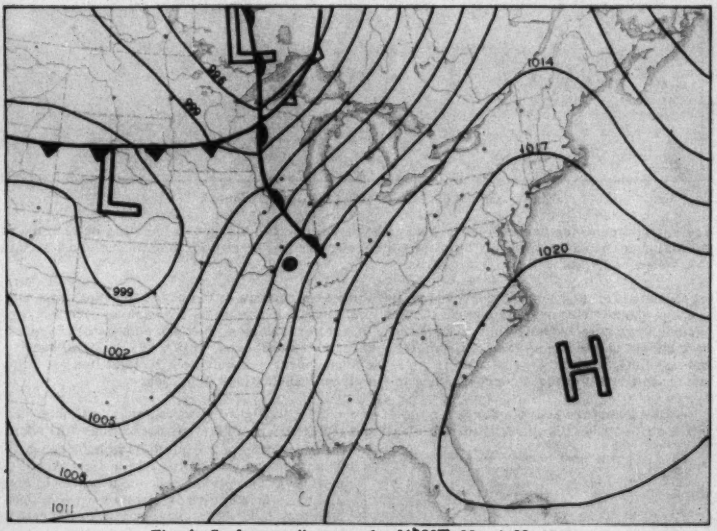

Fig. 4--Surface weather map for 01^h30^m, March 23, 1947

Figures 2 and 3 show pressure curves for Pittsburgh and Terre Haute, which are similar in character to that of Figure 1 with the exception of the time of occurrence of the minimum pressure and the subsequent rises in pressure. The weather situations accompanying these cases were of the same general nature as the conditions prior to the Centralia disaster. In general, those cases where the center of low pressure did not develop in the immediate vicinity or pass over the station under consideration, showed at least the passage of deep troughs and strong cold fronts. Only one case showed high pressure prevailing throughout the period. Most of the cold frontal passages were preceded by strong squall lines and abnormally large pressure drops.

Of the 41 explosions considered in this investigation, 33 occurred in bituminous coal mines and eight in anthracite coal mines. Since it was thought that there might be a difference in the

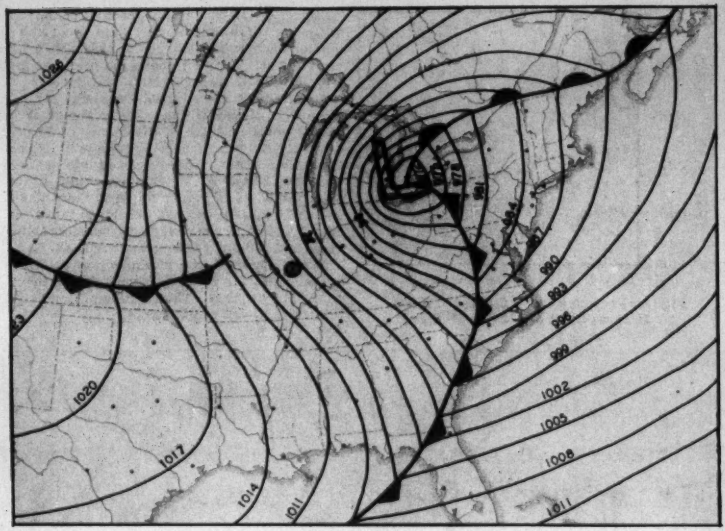

Fig. 5--Surface weather map for 01^{h}30^{m}, March 25, 1947

characteristics of the pressure curves associated with the two classes of mine explosions, the data were also analyzed separately. Thus, results are shown in Figure 6 for bituminous and anthracite cases separately, as well as for all cases.

Since all of the pressure curves have the same axis relative to the day of the explosion, their average should bring out common characteristics, if any. Inasmuch as the various seven-day periods were selected only for the occurrence of a mine explosion, they can be assumed to have been chosen at random as far as barometric pressure is concerned. If there is no significant causal relationship between the two factors, the average curve should be a straight line or, at most, show small changes corresponding to the diurnal fluctuations in pressure.

Considering the average curve for the 41 explosions, in Figure 6, we see that until noon on D-1 the rises and falls in pressure are small and reflect the main diurnal fluctuations. At noon on D-1 a drop of 2.7 mb (0.08 in Hg) occurs. The pressure remains at this lower value until 18^{h}00^{m} on D-day whence it begins to rise and by D+3 is at approximately the same level as it was on D-3. This curve seems to indicate that, generally, mine explosions occur when the pressure is low. Particularly noteworthy is the fact that the pressure fell on D-1, a point which will be discussed later.

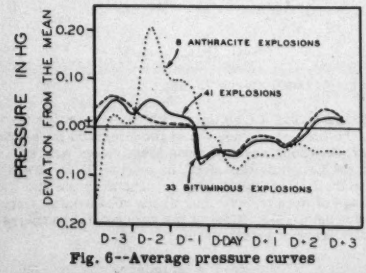

Fig. 6--Average pressure curves

Inasmuch as data relating to bituminious mines are in the majority, the pertinent curve does not differ essentially from the average for all 41 explosions.

The curve for average pressure for the disasters in anthracite mines had its minimum at 18^{h}00^{m} on D-day; 24 hours later than in the

case of the other two average curves. The amplitude of the average anthracite curve is also much greater, but this is undoubtedly due to the smaller number of cases considered. The delayed minimum may well be explained by the different nature of conditions in anthracite mines where gas tends to break out suddenly in a "blower."

In interpreting average curves, we must consider that they tend to accent those pressure changes that are of greatest magnitude and that several significant fluctuations might be cancelled out by one large one in the opposite direction. In order that this might possibly be taken into account and to ascertain that a few large pressure changes did not coincide accidentally and produced what looks like a prominent point in the average curve, the frequencies of certain pressure characteristics were also determined. Those judged to be most significant were: (1) The frequency of net rises in pressure for the period from midnight to midnight on each day, and (2) the number of times the minimum pressure for the seven-day period occurred on each of the seven days.

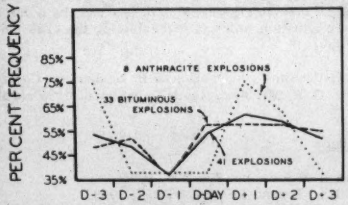

Fig. 7--Frequency of net pressure rises from midnight to midnight

In Figure 7 the per cent frequency of 24-hour net pressure rises brings out the fact that D-1 was actually the day on which the least number of net rises in pressure occurred, or conversely, the greatest number of net decreases coincide with D-1. The anthracite curve shows that drops are in the majority for two days before and including D-day, whereas in the bituminous curve, rises prevailed on D-day. The three curves are fairly symmetrical about D-1. When the 24-hour period from midnight on D-2 to midnight on D-1 is considered more closely, we find that net drops in pressure occurred in 66 per cent of all cases. As regards the magnitude of these pressure drops, net decreases greater than 3.4 mb (0.1 in Hg) were recorded in 50 per cent of all cases.

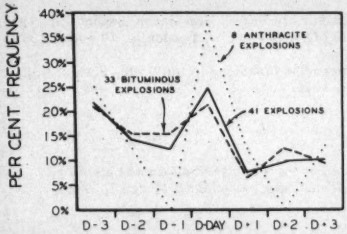

Fig. 8--Frequency of minimum pressures

The frequency with which the seven-day minimum fell on each day is shown in Figure 8. In the case of all 41 explosions, 76 per cent of the minima occurred on or before D-day and 25 per cent were on D-day proper. It is of interest to note that more of the minima in pressure occurred on D-day than on any other day, not only for all cases considered together but also for the bituminous and anthracite explosions separately. Also, the day with the next greatest number of minima was D-3 in all three cases with a dip in the frequency curve in between. This feature of the curves seems to reflect the three-day recurrence of low pressure. The bituminous curve and the curve for all explosions have the least number of minima on D+1, indicating that generally, rises occur on that day. The anthracite curve has the least number of minima on D-1 which would further strengthen the belief that in anthracite explosions the pressure drop was more closely followed by an explosion than in the bituminous cases.

With respect to the time and direction of the fluctuations, these curves show what was expected. The timing in the majority of cases depends on the human element. Once conditions exist that are favorable for an explosion, it may be matter of some hours before an igniting agent is introduced. Operations may not be in progress at the crucial time due to a holiday or a period between shifts. In these cases the explosion is likely to occur soon after work is resumed. The varying lags thus introduced between the time of minimum pressure and the explosion are sufficient to shift the minimum to a period well before D-day and to cause a partial cancellation of the large pressure rises and falls in the average curves. A good example of this effect can be deduced from Figures 1 and 2. In Figure 1 the pressure had already begun to rise before the pressure in Figure 2 had begun its most pronounced fall.

Conclusions--It may be stated that the material considered in this investigation strongly indicates a relationship between the occurrence of coal-mine explosions and the pressure changes accompanying certain synoptic situations. Specifically, sharp pressure falls due to cyclogenesis in the region, passages of deep pressure troughs, deepening of stationary low pressure systems, or the passage of rapidly moving cold fronts with associated squall lines, create conditions in gaseous coal mines that are favorable for explosions.

The meteorologist can forecast such conditions and the mine operator can caution his men working underground of the existence of danger of explosions, or can carry out other precautionary measures. As a matter of fact, such a procedure was followed in England a number of years ago, but was discontinued for unknown reasons. In this respect the following aspects deserve consideration: Mine explosions are few as compared to the number of times that the weather situation is favorable for the accumulation of gas in a mine. Moreover, some explosions do occur with no notable pressure drops. However, these cases are few, so that it would be worthwhile to avoid at least those cases which are occasioned by pressure falls in view of the fact that in the explosions analysed above, a total of 725 lives were lost.

Another point, of psychological nature, which appears to be quite important is the frequency with which warnings of dangerous conditions would have to be issued in the major coal regions of the United States; particularly in the cold season when the passage of deep lows and cold fronts is quite frequent. The constant repetition of warnings might destroy their value as a preventative measure. Also, the possibility must not be overlooked that carelessness on the part of the miners may easily be a function of the same general weather situation which is favorable for the creation of dangerous conditions in mines [HUNTINGTON, 1935].

Acknowledgment--The author gratefully acknowledges the cooperation of H. Neuberger, Chief of the Division of Meteorology; he is also indebted to D. R. Mitchell, Head, Department of Mineral Engineering, for many helpful suggestions.

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THE CENTRAL ALASKA EARTHQUAKE SWARM OF OCTOBER 1947

Pierre St. Amand

Abstract--The earthquake swarm of October 1947 is discussed. Investigation of the activity is described. Intensities in the epicentral region are estimated and an epicenter at Lat. 64°.2N, Long. 149°.0W is assigned. The assigned epicenter of the 1937 swarm is investigated and found to be essentially correct. Photographs of earthquake activity are included along with an isoseismal map and a plot of epicenters.

Introduction

The central Alaska earthquake swarm of October 1947 was another in the series of seismic disturbances which the residents of the Tanana Valley have felt at intervals of approximately ten years, ever since the arrival of the earliest settlers. The 1947 swarm began with a number of foreshocks, some very minute, others violent, culminating in the intense activity of October 16 and the severe aftershock of October 20 GMT. (All dates and times given in this paper are in Greenwich Mean Time.)

Fortunately, for purposes of study, the quakes occurred in early winter when the lake ice and mud bars were thinly frozen. Because of this condition there was severe cracking which facilitated study of the earthquakes. In addition, the large number of aftershocks made an instrumental determination of an epicenter possible.

Investigation

After the quake of October 16, the following investigation was undertaken: (1) Damage in Fairbanks was assessed by William D. Patterson of the United States Coast and Geodetic Survey and members of the College Geophysical Observatory staff. (2) A questionnaire was sent to all postmasters in interior Alaska. (3) Requests for information were broadcast over the local radio station and were published in the newspapers. (4) Flights were made to observe surface evidence. (5) A helicopter trip was made to the region most severely affected. (6) Foreshocks and aftershocks were scaled and plotted. (7) A geological investigation was initiated, which is to be the subject of a paper by R. C. Ragle, Chairman of the Geology Department of the University of Alaska.

Observations

College--The first impulse of the largest shock was recorded on the McComb-Romberg instruments at College at $02^h10^m00^s$. The mirror of the N-S instrument was immediately knocked off the pivots. For several minutes the motion was too rapid to record on the other instrument, even though Ernest Wolff, Observer-in-Charge, who was in the seismograph room at the time, immediately increased the lamp voltages on the instruments. It was subsequently discovered that the prism systems on both instruments were disaligned by the shock. Everyone in the University buildings ran outdoors, as did most of the inhabitants of Fairbanks. The damage at College was slight, consisting of some overturned acid bottles in the Chemistry Laboratory. The magnetographs at the Observatory were thrown completely out of adjustment. The magnetic balance of the Z-variometer was thrown from the supports and the H and D traces were shifted, necessitating complete realignment of the instruments. This realigment was completed just before the shock of October 20 which again threw them out of adjustment.

Fairbanks--In Fairbanks, many objects were thrown from shelves. This resulted in heavy damage in liquor and grocery stores. Many of the merchants, being aware of the earthquake hazard, have wires permanently stretched across the front of their shelves to prevent the fall of bottled goods. These reduced the loss. Furniture was moved about and a number of relatively stable objects were overturned, including some large carbon dioxide bottles at the Pepsi-Cola plant.

Increased turbidity was reported in many wells. The Brazil family, residing between Fairbanks and College, reported an increase in their well water. The well at the Experimental Farm began producing copiously for the first time since it was drilled.

Trees and poles were shaken violently. Power lines near the Experimental Farm were shorted by the swinging of the wires. The public was alarmed by the quakes which were occuring hourly. After the violent shock of October 16, the author made a broadcast, telling what was already known about the earthquakes and advising the public as to the proper precautions to take in the event of another shock. Rumors had been circulating that an even more violent shock was expected about ten o'clock that night. It was carefully explained that such a rumor was groundless and that the specific time at which an earthquake would occur could not be predicted. Nevertheless, tension continued among the innabitants for several days. One nervous individual moved to the States.

Tanana, Tolavana, and Kantishna Valleys--A plot of the aftershocks revealed that the epicenter appeared to be near the point where the Nenana River entered the Tanana Valley. R. C. Ragle, the author, and members of the Geology Department made a series of flights to verify the location and seek surface evidence. Intense cracking of lake ice and river bars was noted from Chena Bluffs to Bean Ridge on the Tanana River and from Clear on the Nenana River almost to Livengood on the Tolavana River. According to Ragle, the most severe cracking took place on the Kantishna River. At Nenana, cracks appeared at various places in the town.

On October 22, Wolf, Ragle, and the author made a flight in an Army B-25 up the Tanana River to Snag, Y. T., thence to Dawson, down the Yukon to Circle, across country to Rampart, then down the Yukon to a point opposite Fish Lake, and back up the Tanana to Fairbanks. The flight revealed that lake ice along the Tanana was cracked all the way to Snag. Cracks in lakes along the White River and Yukon were very scarce until Rampart was reached. Here the cracking began to reappear, although it was much less severe than along the Tanana River. There was some dispute as to the origin of the cracks; but Ragle, basing his conclusion on several years of bush flying in the Territory, attributes the cracking of the lake ice to seismic causes. This appears likely, as the cracking diminished with distance from the epicenter, and in the Yukon Territory there were many lakes with no fissures. The lake ice near Clear and along the Wood River was not only cracked, but crushed and piled up upon itself.

Investigations in the epicentral region

After defining the area in which the most intense activity took place, the author made a flight to this region in an Army helicopter. The trip was made ten days after the quake of October 16. Fresh snow had fallen on the day preceding the trip, and although it partially filled surface cracks, it did not seriously hamper observations.

Fracturing in bars--A landing was made on a Tanana River bar about 15 miles downstream from Chena Bluffs to investigate the cracking. The cracks measured up to 22 inches in width at this place, were several hundred feet long, and were between six inches and a foot in depth as shown in Figures 1 and 2.

The surface beneath the cracks was reasonably flat, and it is believed that the cracks were caused by movement of the frozen surface layer of the bars, set up by the quake in the unfrozen alluvium beneath. The frozen upper layer appeared to have cracked and slipped in the direction of the river bed or along any downward grade. Undoubtedly, the material beneath settled as it sluffed into the depths of the river. The displacements indicated by the cracks are not, therefore, indicative of actual ground movement during the quake, which was probably less. In places, the frozen layer moved in such a manner that two large blocks were brought together resulting in pressure ridging as is illustrated in Figure 3. The photograph was made from a height of 15 feet. The top of the ridge is about three feet from the flat ground beneath. This would indicate a movement of the thin surface layer in excess of three feet. These pressure ridges were less frequent than the cracks and appear to be confined to the lower places on the bars.

Landslides--Several rock slides were observed about halfway between Nenana and Fairbanks on the Tanana River. The Alaska Road Commission also reported slides along the Richardson Highway at miles 51, 66, and 81, measured from Fairbanks.

Berg--The station house at Berg creaked loudly on both October 16 and 20. The quake of October 16 was felt by some men resting in a railway car and caused a pile of ties to fall over. A train crew a short distance from there was inclined to stop the train to investigate the shaking. No damage was observed at the station house, which is a well-built frame structure. The only other buildings there are small log cabins. Canned goods fell from the shelves, and water was splashed from the teakettle. The people were firghtened, but the only person to run outdoors was a woman with an infant.

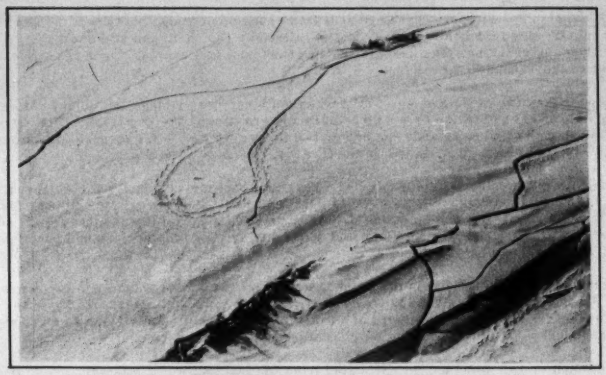

Fig. 1--Cracking in river bars

Fig. 2--Cracking in river bars

Fig. 3--Pressure ridging in river bars; taken from a height of 15 feet

Slides along the railroad--There are at least two incipient slides between Mahon and Nenana which should be cared for before they block the railroad. The earth has slid down a little giving the appearance of cracking. The potentially dangerous spot is a short distance from Nenana on the north side of the Tanana River.

Nenana--The town of Nenana was well shaken but structural damage was slight. Most of the buildings in town are old frame or log structures and are earthquake resistant. There were many cases of stuck doors and cupboards and one or two broken windows. A recessed wall mirror at Vance Hit's was cracked. Wall panels in the C. A. A. houses showed cracks.

There was much damage to store stocks. Furniture was moved about, cups were shaken off cup hooks, and many unstable objects were overturned. Settling of the ground and poor foundations seem to account for all the damage to buildings. In one liquor store, it was discovered that the bottles were still scattered over the floor and that a stud to which the shelves had been fastened no longer reached the ceiling, but was about one and one-half inches too short.

Several cracks were noticed in the ground, some near the school house, in a farmer's field near the Nenana River, and two in the living area of the C. A. A. settlement. These latter-mentioned cracks were about three-quarters of an inch in width and at least a hundred feet long. One crack passed under the utility building which was thrown out of plumb.

The amount of movement can be estimated from the fact that water was splashed in quantity out of a tank ten feet six inches in diameter, eight feet six inches high, mounted on a concrete foundation and filled to within six inches of the top.

The most remarkable feature of the activity at Nenana was the behavior of well water. At least three wells equipped with pitcher pumps gave water spontaneously after the quake of October 16. The pump at Thomas Albert's house was broken off the pipe and water continued to issue forth to a height of six inches for several minutes. R. H. Sunnyboy reported by letter that the big quake was preceded by a rumbling noise and was so severe four miles south of Nenana that it was difficult to stand. The ice on the water holes fractured, and he observed one crack along the railroad track. When he returned to Nenana, he found more cracks about one-half inch in width. The pump at his house had been discharging water freely. This was somewhat of a surprise because the well had never produced much water.

Clear--The activity was intense at Clear. It was felt by a man driving a caterpillar tractor. The buildings creaked and groaned. The weather observers stated that it was with difficulty that they were able to stand and that they were forced to hold onto the instrument shelter to support themselves. A seven-ton steam boiler moved about on a truck and threatened to fall. Vehicles which were not in gear or with the brakes set moved about as much as two or three feet. A carbon dioxide container and fire arms stacked against the wall fell over. Barracks bags swung through a two-foot arc.

The ground motion felt elliptical and was estimated by all to be at least two inches, although the average guess was somewhat larger. The estimated duration of perceptible ground motion varied from ten sec to 30 min. There was also considerable difference of opinion as to the direction of movement. All heard noise during the shock.

The buildings at Clear are of the prefabricated type common in Army camps and many of them were thrown out of line and level. The rear wall in the Post Exchange building was pulled about two inches from the rest of the structure.

Records of test wells drilled at Clear showed no significant change in water level except for a seasonal drop due to freezing of surface supplies.

Browne--The slump of the railway previously reported at Browne was observed from the air, but unfortunately no landing could be made. From conversations with the railroad people and a previous knowledge of the terrain, it appears that the slump is a recurring condition, possibly aggravated by the earthquakes, and is not indicative of actual ground movement.

A few land slides in the Nenana gravel banks may be seen between Browne and McKinley Park Station.

Ferry--At Ferry the station house moved violently. Water was splashed from a pail filled to within four inches of the top. All the closet and cupboard doors appeared to be stuck as a result of

the quake. Furniture moved about and unstable objects fell over. Everyone ran outdoors. People reported feeling many aftershocks very strongly.

Healy Forks--Mrs. Fern Hollis, Postmistress at Healy Forks, reported that in the Suntrana Coal Mine, some four miles distant, mine timbers were cracked, loud noises were heard, and boulders were shaken from the hillsides. The banks around there are very steep and it would be easy to start a landslide.

McKinley Park Station--At this station a number of panels in the very well-built station house and hotel were pulled about one-half inch from the walls. A beam in the kitchen, previously reported cracked, was not really cracked but only appears so because the plywood used to face it has pulled away from the ceiling. Unstable objects were overturned and furniture moved slightly. A number of objects fell from shelves.

Railroad slump near mile 351.4--Perhaps the most noticeable disturbance which might be attributed to the quake was a sink in the railroad tracks at mile 351.4, about a mile and a half north of McKinley Park Station. Here a sort of landslide caused the tracks to sink over 8.7 feet in less than 20 hours (see Fig. 4). It is difficult to see where the dirt went for it appears to have sunk straight down. The river carried no silt immediately below the slump, and the river bank

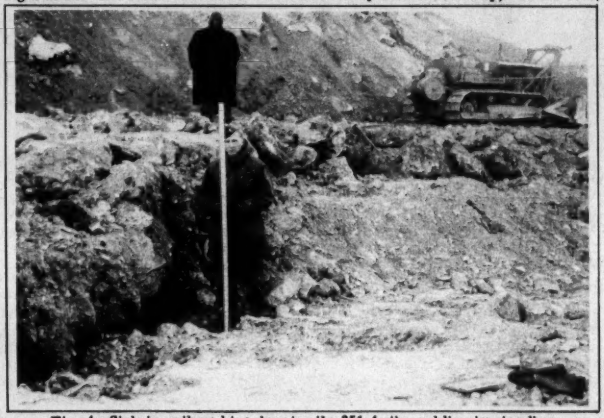

Fig. 4--Sink in railroad tracks at mile 351.4; the soldier is standing on the bottom of the sink; the other man is on the former grade

had not been altered noticeably. It is possible that the earth at this point is slumping straight down, causing the mass beneath to bulge; but there is no evidence that this is the case. A melting ice lense might explain the phenomenon. The slump is located on a curve only 100 feet or so from a trestle. This trestle is in danger if the sliding continues (see Fig. 5).

R. A. Sharood said that the trouble began the first week in October and grew progressively worse. He said that this particular spot has always given trouble. The earth is very unstable, and it appears likely that the earthquakes may have aggravated the sliding. There was a large number of shocks earlier in the month, including a very strong one the day of the big slide. Several other slumps were noticed between mile 351.4 and McKinley Park Station. While none of these is great enough to prevent operation of the railroad, they are all hazards. The track is laid on the slope of a steep gravel bank which lines the west wall of the canyon. It is strongly recommended that the roadbed at this point be moved farther back into the hill and placed on solid rock. A combination of increased traffic, spring thaws, and agitation by earthquakes will certainly worsen the situation. If this section is not put on a more sound foundation, the whole section may fall several hundred feet into the Nenana River.

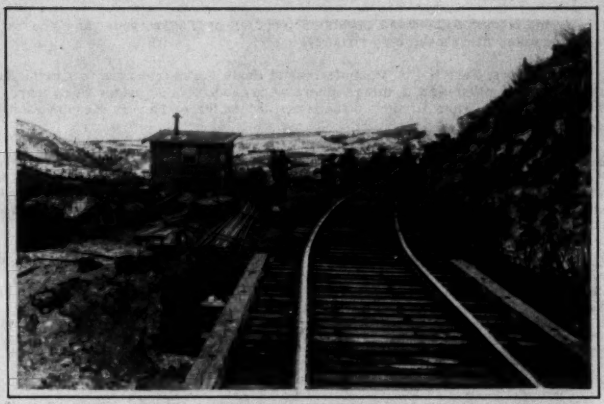

Fig. 5--Sink at mile 351.4 on the Alaska Railroad; the soldier is standing on the former location of tracks; the trestle is the one described in this report

Questionnaire returns

The response to the questionnaires was immediate and very commendable. With the sparse population of Alaska to secure information it is not possible to obtain a very clear picture of the earthquake intensity, but the interest and eager co-operation of the people of the Territory made it possible to determine the extent of the felt area. The questionnaire consisted of a copy of the Modified Mercalli Scale and a postal card. The people were asked to estimate the Mercalli intensity and list on the postal card any phenomena noticed by them and their neighbors. Some correspondents questioned as many as 20 people before drawing their conclusions. Many unsolicited reports were furnished.

The isoseismal lines drawn on Figure 6 are based on these reports at the greater distances and on observations by the Observatory staff at places near the epicenter. As would be expected, there is considerable scatter in the estimation of the intensity. The chief trouble in closing the isoseismal lines arises in the extremely strong reports from Beaver, Circle City, Central, Circle Springs, and Eagle on the Yukon River. Noel Ross of Beaver reported cracking in the river bars there and very violent activity in general. The postmaster at Eagle was interviewed on his arrival in Fairbanks a short time after the earthquake. He told of cracks in the walls of the postoffice building and of water being splashed from buckets and barrels. The stories from Circle and Central corroborate their opinions. Ragle thinks that this may be attributed to a local earthquake triggered by the stronger shock. There is no possibility of checking this instrumentally. The author has tried to interpret the data so as to give the most reasonable isoseismal lines, and they should be regarded as rough approximations.

The felt area is relatively well defined to the south and west. The sparse population to the north and east makes the boundary uncertain in these directions. To the south, the earthquake was felt at Kasilof, Seward, and Moose Pass. It was not felt at Homer. It was felt at Koyukuk on the Yukon but was not felt at Nulato or Kaltag. Father Convert reported that the natives at Hooper Bay felt the shock. Hooper Bay is much farther west than Kaltag. The residents of Wiseman in the Koyukuk region felt the shock, while those at Old Crow near the Canadian boundary on the Porcupine River did not. The people at Carmacs in the Yukon Territory felt it. This evidence would make it seem that the mean felt radius was about 500 k.

The following are verbatim quotations from some of the questionnaire cards:

Tanacross--Intensity 3, School building being two story log construction shook pretty bad no damage exept some window glass broken.

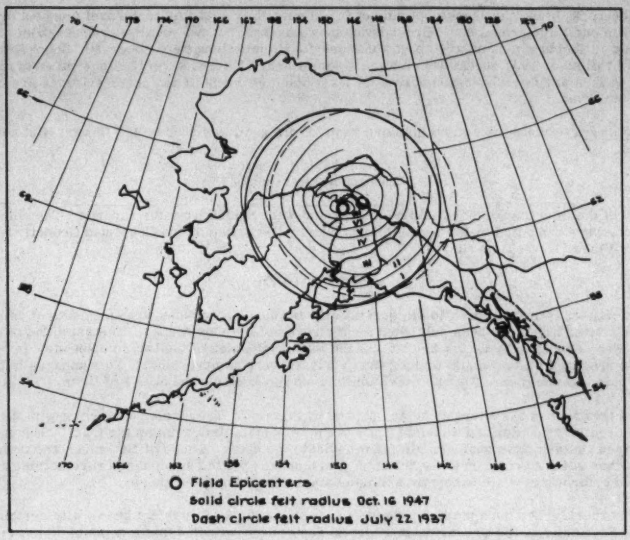

Fig. 6--Isoseismal map of central Alaska earthquake of October 16, 1947

Rampart--Possible force 6 but no damage reported. Native scared pretty bad. Small waves in Yukon. Radio poles and trees swayed. One pendulum clock stopped for some time started running after disturbance. Noticed by everyone but as all dwellings are log cabins of solid construction there was no damage reported.

Gulkana--Felt quite noticeably by all --- dishes, doors, and windows disturbed. All suspended objects and trees swayed violently.

Ester Creek--Many articles (bottles and tins) were shaken from shelves and some rolled across the floor, but the loss consisted only of one half pint jar of mayonaise broken to bits! We observed clouds of dust where the dirt was shaken down on the roads across on the hill. Some of the residents had a number of dishes, etc. broken. All badly frightened but no one hurt.

Chicken--Last about ten seconds. Splashed water in 50 gallon drum about three-fourths full but did not spill over the slides. Cooking utensils shook for nearly a minute hanging from hooks. Log cabin shook in an easterly-westerly direction. No noise. A man outside sawing wood said he didn't feel it.

Koyukuk--The earthquake was felt here shortly after four pm. I had just finished practicing the piano and wondered why it should vibrate. Mr. Vernetti at the store thought the light plant had started.

Central--Cars standing in seven inches new snow moved two inches. Heavy motor sitting on ground almost rolled over. Trees and radio poles swayed approximately ten feet. No damage reported. People left buildings. Duration three minutes.

Beaver--Was heard coming before it struck here. First blow came from south, subsequent forces moved suspended objects east and west as well as north and south. Raised right limit cut-banks of river at Beaver eight inches immediately as evidenced by ice at shoreline. Made open leads in river ice. Changed course of water in one right limit slough of Yukon below here. Made high willows swing round and round. An Army Survey party 17 miles north of Beaver encamped

above bedrock, heard the shocks but did not feel them. Pulverized frozen gravel (current or recent freeze) in one large gravel bar. Ground was snow covered, but two parallel cracks, about a foot wide and 12 feet apart, in an arc about about one-fourth mile long were observed. Shocks were not quite as violent as 1937 shocks which were also felt here. Caused several minor cases of dizziness. Quakes are fairly common here---at least one a year. Sluff and crack evidence are commonly observed.

Tetlin--Everything was move in store some of dry good was drop on the flower. But none damage.

Location of aftershocks

All of the aftershocks that could be interpreted were scaled from the records. The epicentral distances were computed by the formula furnished by the United States Coast and Geodetic Survey with the Visser travel time charts:

$$\Delta = 10.5\ (S\text{-}P)\ \text{Km}$$

The accuracy of this operation is questionable because no reliable measurements of seismic wave velocities have ever been published for the rocks of interior Alaska. The azimuths of the shocks were computed by taking the ratio of the initial impulses of the two components. In plotting the 1947 shocks it was assumed that all first arrivals were compressions. This appears to have been a sound assumption. The one exception is a small shock plotted near Big Delta.

The locations of the aftershocks are plotted in Figure 7. The circles are drawn with the computed epicenter as center and a radius equal to the maximum deflection on the trace. The quakes occuring in October have numbers affixed to indicate the dates. Those of November are indicated by N. Other earthquakes carry the full date. Earthquakes plotted as assumed rarefactions are indicated by brackets while uncertain azimuths are indicated by parentheses.

No correction has been made for the depth of the shocks as this is not known with certainty. Charles F. Richter of the California Institute of Tecinology indicated that a depth of 50 km might be appropriate for the shock of October 16. This would cause the horizontal distance to the epicenter as interpreted from the seismograms to appear too great. Since there are no other seismographs in interior Alaska, it is not possible to obtain an accurate fix and this matter cannot be resolved at present.

The distribution of surface cracking shown by the irregular dashed line would indicate that the whole pattern of aftershock locations might be moved closer to College. The geology of the valley could be responsible for this situation, as the vicinity to the south of the dotted region is a gravel outwash plain terminating in the foothills of the Alaska Range. The soil within the dotted area is for the most part deep deposits of silt, muck, and other alluvial matter interspersed with gravel beds. The silt is very fine and when mixed with water is unstable unless frozen. Therefore, cracking would be easier in the region enclosed by the dotted lines than to the south where the ground is more stable. In fact, all the cracks examined by the author occurred in silt or in gravel bars underlain by unfrozen silt. The cracks in the town of Nenana were partly in filled land and partly in soft, silty soil.

The shocks of the February 1948 series are included in Figure 7, but they may or may not be a part of the October series. Information furnished by people living along the Richardson Highway substantiates the general locality.

1937 swarm

Copies of a number of seismograms containing aftershocks of the earthquake of July 22, 1937 were furnished by the Director of the United States Coast and Geodetic Survey. As many as could be scaled were plotted on Figure 7. It is apparent from the records that the epicenters for that swarm were essentially in the place indicated by BRAMHALL [1938] and coincide reasonably well with the surface evidence.

One feature of these shocks was that they were not uniformly compressions or rarefactions. The 1937 shocks are indicated by the dotted circles. There is no basis for assigning the 1937 shocks to the 1947 epicenters. Bramhall has indicated a felt area slightly less than that of the 1947 shocks. This may be due to a more extensive investigation in the latter case. Most people are of the opinion that the main shock of the 1947 series was of slightly greater strength than that of 1937.

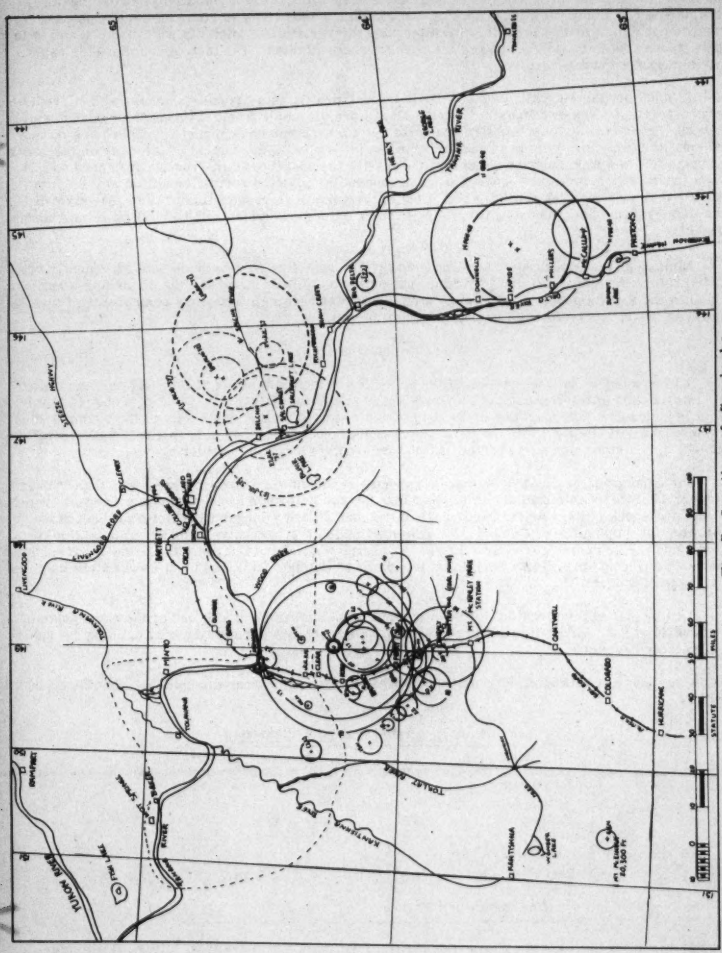

Fig. 7--Locations of aftershocks

General

Earthquake investigation in Alaska is difficult. There is only one set of seismographs in interior Alaska, and these are teleseismic instruments of too low a sensitivity and too cramped a time scale to study weak local shocks, and too high a sensitivity to study the major shocks. The sparse population makes it difficult to determine the variation of intensity with distance and to locate the epicenter by finding the region most severely affected. The lack of roads makes expensive air transportation a necessity.

In addition, the Mercalli Intensity Scale is designed for more populous areas with conventional construction. The dwellings in interior Alaska are all small frame structures or one-story log cabins. There are no masonry structures except a few reinforced concrete. There are no monuments or tall factory chimneys and no buried water mains. Assessment of intensity on the basis of being felt in a motor car is ridiculous because of the condition of the roads. It is hard to tell if railroad rails have been displaced a small amount because the normal condition of the Alaska Railroad is such that one could not tell if the earthquake were responsible or not. The staff of the Geophysical Observatory is attempting to work out a scale which will be applicable to Alaskan quakes.

Almost all the shocks were accompanied by low, rumbling noises which could frequently be heard before the shock was felt. The interval between the first sound and the shock was about equal to the S-P interval, and the sound probably came from high frequency components of the P waves, which were often not strong enough to be felt.

Conclusions

It is concluded that the location of the epicenter of the main shock of the 1947 series is near the intersection of the Nenana and Tanana Valleys at approximately Lat. 64°.2 N, Long. 149°.0 W. This is based on a consideration of the intensities reported by the inhabitants of the region and on the instrumental studies. For the reasons previously stated it is possible that this location will be subject to revision when more can be learned from aftershocks in the future.

The earthquake of October 20 was everywhere reported to have an intensity less than that of October 16. This would lead one to suspect that the two may have had a common epicenter. Some of the aftershocks following the earthquake of October 20 had a longer (S-P) interval than those following the earthquake of October 16. This may indicate progressive faulting. It may also indicate that the epicenter of October 20 was farther up the Nenana Canyon. This view is strengthened by the report from Healy Forks that the quake of October 20 lasted for a longer time than the quake of October 16.

Richter placed the magnitude of the earthquake of October 16 at 7.3, and of the earthquake of October 20 at 6.8. These values were based on the Pasadena seismograms only and may be subject to later revision.

A summary of estimated Mercalli intensities for the region near the epicenter is offered in Table 1.

Table 1--Estimated Mercalli intensities

Place	Mercalli intensity
Fairbanks	7
Berg	7 +
Nenana	8
Julius	8 +
Clear	8 +
Ferry	6 + to 7
Healy Forks	6
Mt. McKinley Park Station	6

Reports from the railroad people were used to estimate the intensity at Julius. Roadmaster Fleming drove over the rails in that vicinity shortly after the earthquake of October 16 and reported that they had been bent slightly. The other reports were similar to those from Nenana.

It appears likely that if there had been any extensive development of the area near the epicenter, such as in a large city, the damage would have been great.

Recommendations

It is strongly recommended that any construction undertaken in the Tanana Valley be designed to withstand violent earthquakes and that whenever possible construction on silt should be avoided.

It is further recommended that the Alaska Railroad reroute the tracks through the Nenana River Canyon in such a way as to avoid building on the gravel beds which line the canyon walls. Although earthquakes aggravate the tendency toward sliding, the real cause lies in the instability of the ground; and with increased traffic the situation will become dangerous.

There is no way of telling when or where another earthquake swarm may appear, but in view of the past history of the Tanana Valley more earthquakes may be expected. It must also be remembered that in addition to the main shock there were over three hundred aftershocks. The two largest were of destructive intensity and several smaller ones reached a Mercalli intensity of 5 at Fairbanks, some 50 miles from the epicenter. This might be a good sign, indicating that the crust is too weak to accumulate sufficiently large strains to produce an extremely destructive earthquake.

It is recommended that further study in the seismicity of Alaska be carried out in view of the anticipated increase in territorial population and the intended expansion of Alaskan defenses by the Federal Government. It is felt that the earthquake situation presents a real hazard to large airbases.

Adequate instrumentation should be installed at the University of Alaska with auxiliary stations at Mt. McKinley Park, Big Delta, and Anchorage. A seismograph specially adapted to the study of local quakes is being designed at the College Geophysical Observatory. In addition, an extended geological study of the region should be made.

Acknowledgments

Thanks are extended to C. E. Bunnell, President of the University of Alaska, for permission to carry out this investigation. A major portion of the work in arranging this investigation and in accumulating and reducing the information contained herein was done by Ernest Wolff, Director of the College Geophysical Observatory. Without his help it would have been impossible to prepare this report. Acknowledgment is also made to Lloyd Watnee, Commanding Officer of Ladd Field, and to Major Rudser, Base Engineering Officer, for arranging transportation and housing. Charles Weir of the Tenth Rescue Squadron, the helicopter pilot, was very cooperative and helped with the survey in addition to flying. Major McBride at Clear was very helpful and hospitable. Mr. Tankahov of Fay, Spofford and Thorndike was also very helpful.

R. C. Ragle, Chairman of the Geology Department, spent much time in discussing the geological aspects of the problem with the Observatory staff and helped with many phases of the investigation, including much of the aerial reconnaissance.

The personnel of the United States Coast and Geodetic Survey were very cooperative. The Director made records of the 1937 shocks available. W. D. Patterson and Allen Rugg aided in the earlier phases of the investigation.

Thanks are also due the Northern Commercial Company for the use of their aircraft, the editors of the Fairbanks Daily News-Miner and Jessen's Weekly for publishing requests for information, and to the manager of Radio Station KFAR for broadcasting repeated requests for information.

Harold Cronin, Mrs. John Wynne, and W. R. Rolfe prepared the questionnaires and aided in the stenographic work. Dan C. Wilder prepared Figure 6.

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STATISTICAL DISTRIBUTION OF DROP SIZES AND THE OCCURRENCE OF DOMINANT DROP SIZES IN RAIN [a]

Robert E. Horton

(Posthumous publication, arranged by Richard Van Vliet)

Abstract--In accordance with a model of a thunderstorm developed by the author [HORTON, publication pending], the ascending air current in a convective storm separates raindrops formed in the hail and snow stages into two components. The larger drops fall directly from the ascending air current, while the smaller drops are carried upward into the outflow layer and precipitated as peripheral rain.

In this paper various series of observations of raindrop size distribution are analyzed and it is found that the observed characteristics of statistical distribution of drop sizes in different parts of the storm and for rain, sleet, and hail, are in agreement with the results which follow from the operation of the thunderstorm model described.

DEFANT [1905] suggested that most raindrops result from the union of drops of a given initial size, so that the drop volumes are approximately integral multiples of this size. It is shown that there is a tendency toward the occurrence of dominant drop sizes which are roughly multiples of a given initial size. This apparently results from the lateral coalescence of drops of the same size as they fall at the same speed.

Drop-size distribution--BENTLEY'S [1904] data of drop-size distribution in 51 storms and for samples taken from the east, central, and western portions of each storm are given in Table 1. The percentage of the total number of drops of diameter larger than the upper limit of each class size is given in the last column of the table. These data, together with similar data from Lenard's observations (see Table 2) and LANDSBERG and NEUBERGER [1938] for sleet are shown graphically on Figure 1. These distribution curves are closely similar in form but Bentley's shows much higher percentages of numbers of large drops. It seems certain that his drop sizes, which were determined from flour pellets produced by the drop, are considerable in excess of the true diameters, especially for large drops, which formed greatly flattened pellets. Note that Figure 1 shows drop-size distribution, not distribution by volume.

Table 1--Relative number of drops of different size limits (after BENTLEY [1940])

Range	Diameter of maximum size	Portion of storm sampled				Cumulative		
		East	Central	West	Average	Upper limit of diameter	Total number larger	Per cent of total
in	mm					mm		
1/30	0.847	15	20	21	18.7	0.00	134.7	100.0
						0.847	116.0	86.6
1/30-1/18	1.42	51	46	46	44.0	1.42	72.0	53.8
1/16-1/8	3.18	42	42	40	41.7	3.18	30.3	22.6
1/7 -1/5	5.08	26	23	23	24.0	5.08	6.3	4.7
2/5	...	4	8	7	6.3	...	...	...

The large portion of total volume contained even in a relatively small number of large drops is shown by Table 3. It requires only four drops per minute 1/5 inch in diamter, falling on one sq inch to produce a rain intensity of one in/hr, whereas it requires about 65 drops per minute of the ordinary average diameter, two mm, to produce the same result.

If the number of drops of different sizes in a rain is known, the percentage of the total volume of the drops having diameters greater than a chosen size d_c can be determined by summation of the products of the volume per drop and the number of drops of different diameters.

[a] The completion, preparation, and publication of this paper (No. 1 of a series) were made possible by the funds available under a special bequest of the late Robert E. Horton--Ed.

Table 2--Number of raindrops of various sizes in nine showers[a]

Drops			Number of drops per m^2 per second[b]									Mean
Diameter		Volume	1	2	3	4	5	6	7	8	9	
mm	in	mm^3										
0.5	0.019	0.066	1000	1600	129	60	0	100	514	679	7	454.3
1.0	0.039	0.523	200	120	100	280	50	1300	423	524	233	358.9
1.5	0.059	1.77	140	60	73	160	50	500	359	347	113	200.2
2.0	0.079	4.19	140	200	100	20	150	200	138	295	46	143.2
2.5	0.098	8.19	0	0	29	20	0	0	156	205	7	46.3
3.0	0.118	14.2	0	0	57	0	200	0	138	81	0	52.9
3.5	0.138	22.5	0	0	0	0	0	0	0	28	32	6.7
4.0	0.157	33.5	0	0	0	0	50	0	0	20	39	12.1
4.5	0.177	47.8	0	0	0	0	0	200	101	0	0	33.4
5.0	0.196	65.5	0	0	0	0	0	0	0	0	25	2.8
All sizes, total			1480	1980	486	540	500	2300	1840	2190	500	1312.9
Rate of rainfall mm/min			0.09	0.06	0.11	0.05	0.32	0.72	0.57	0.34	0.26	0.28

[a]After P. Lenard, Meteorological Glossary, p. 335.
[b]Numbers 1, 2, and 3, ordinary rains; numbers 4, 5, and 6, convectional and thunderstorm types; numbers 7, 8, and 9, heaviest, medium, and terminal periods in a rain of cloudburst intensity.

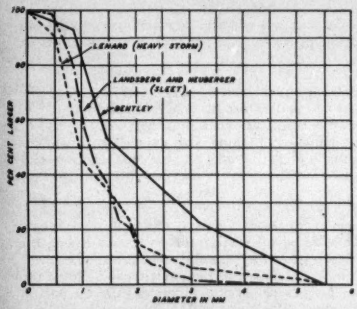

Fig. 1--Drop-size distribution in rain

Table 3--Diameter, suspension velocity, and volume of raindrops (after LAWS [1941])

Drop diameter		Suspension velocity		Volume per drop
mm	in	m/sec	ft/sec	mm^3
0.5	0.019	2.30	7.54	0.066
1.0	0.039	4.15	13.61	0.523
1.5	0.059	5.50	18.04	1.77
2.0	0.079	6.58	21.58	4.19
2.5	0.098	7.40	24.27	8.19
3.0	0.118	8.02	26.31	14.2
3.5	0.138	8.50	27.88	22.5
4.0	0.157	8.85	29.03	33.5
4.5	0.177	9.08	29.78	47.8
5.0	0.196	9.25	30.34	65.5

From the data used in preparing Figure 1, curves showing the percentage of total volume of rain falling in drops exceeding different diameters were obtained, as shown on Figure 2.

If drop-size distribution were the same in the peripheral and central portions of the rain splash, then these exceedance percentages for a given storm would also represent the exceedance percentages for the entire volume of rain falling per unit of time over the rain splash area. As a rule there are variations in the drop-size distribution in different parts of the storm, larger drops predominating in the earlier, and smaller drops in the later, stages.

Bentley's data (see Table 1) comprise complete or nearly complete sets of samples from nine general rainstorms, 23 thunderstorms, and 19 rain showers. East and west portions of the storm, as given in Table 1 correspond approximately to the front and back of peripheral rain. Bentley concluded that "...in general the very small drops increase in number from the east (front) to the west (back) edge of the storm," and that drops of other sizes, each, as a rule, shows a progressive increase toward the center of a storm but then decreases toward the west portion. If only core rainfall occurred, then with only those drops falling from the core which have suspension velocities exceeding the ascent velocity in the part of the convection tube where they are formed, rain would consist of large drops during ascending gusts and small drops during lulls. Ascending gusts of different velocities would account for the occurrence of drops of all sizes in any part of the rain splash. Drops falling from the core may absorb other smaller and slower drops swept in

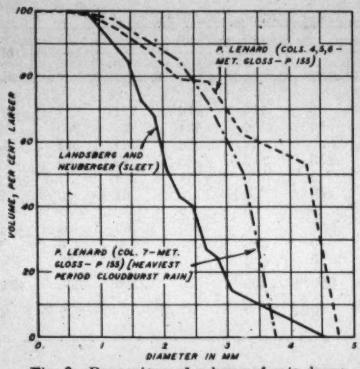

Fig. 2--Percentage of volume of rain drops exceeding a given diameter

their paths. This effect is probably small, for two reasons: (1) Core rainfall comprises initially larger drops. If they are over 5.5 mm in diameter they break into smaller drops. For drops between two mm and five mm in diameter, the maximum difference of suspension velocity is about two m/sec. With suspension velocity of eight m/sec, a larger drop of core rainfall will not overtake a smaller drop below it unless the larger drop is initially within a distance not more than one-fourth the height of fall at the start, and a much smaller distance if the drops are of appreciably the same size. (2) If the upper raindrop is much the larger, the smaller drop is likely to be pushed aside by the compression of air in front of the approaching larger drop.

Drops which later become peripheral rain are those arriving at the outflow level with less than a certain critical size d_c, depending on the ascent velocity in the air current producing them. Drops of this critical size which rise to the top of the outflow layer cross the paths of all smaller coincident droplets. A drop which rises one-half way through the outflow layer before it is deflected outward crosses the paths of one-half of the coincident drops, and so on. Drops of the critical size can readily collide with other drops of the same or slightly smaller sizes in the outflow layer, as will be seen from Figure 3A, while drops of a given size cannot overtake drops of the same size in descending through the core.

Core rainfall apparently consists mostly of drops which have not been derived from the breaking up of larger drops nor from the coalescence of smaller drops. For the storm as a whole, all sizes of drops will occur as core rain because of the alternation of high and low velocities in wind gusts. At a given moment the size of drops comprising core rainfall will depend on the ascent velocity and the sequence of ascending wind gusts. It will be seen that drops occurring as core rainfall are mostly generated as such but must be of sizes that can fall through the ascending current of air.

Drops precipitated as peripheral rain are derived from smaller drops, either initial drops or drops resulting from the union of larger drops which have been carried aloft in the ascending air in the storm core. As they reach the outflow level they are generally smaller than drops of coincident core rain. Drops of peripheral rain near the inner boundary of the peripheral belt are often the result of cross-collisions in the peripheral ring. Larger drops of peripheral rain are concentrated near the inner edge of the peripheral belt and smaller and smaller drops occur at increasing distances from the core. These phenomena are illustrated by Figure 3A, which shows a cross-section of a convective thunderstorm.

The velocity of storm travel is governed chiefly by the velocity of the air in the cover layer. If this is greater than the component of wind velocity in the outflow layer in the same direction, then the peripheral belt of precipitation mnop, instead of being concentric with the convection tube, will be eccentric and will appear in cross-section somewhat as shown by the lines qrst. As a result, the belt of peripheral rain at the front of the storm will be narrower than at the back of the storm. The predominant drop sizes in a cross-section of the storm in the direction of travel will be somewhat as shown by Figure 3B. If Figure 3B is converted into a drop-size distribution curve, then the two summits will be combined and the drop-frequency curve will appear as shown by Figure 3C. This closely resembles the drop-size distribution of LANDSBERG and NEUBERGER'S [1938] drop-size data for sleet (see Fig. 4). The data were grouped by class increments of 0.2 mm diameter (see Fig. 4).

Since raindrops precipitated as core rain and peripheral rain orginate in different waves, a difference of drop-size distribution in the two cases is to be expected. Many more data on drop-size distribution are needed before a definite conclusion can be reached. The following examples indicate that there is a difference.

The frequency distribution equation

$$f = cd^2e^{-kd^2} \quad \ldots\ldots\ldots\

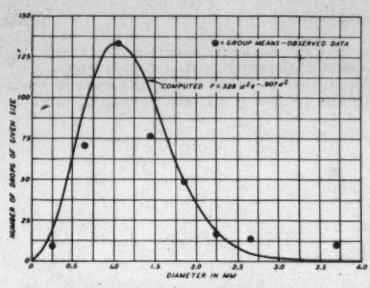

Fig. 4--Size distribution of sleet drops from LANDSBERG and NEUBERGER [1938]

(Average surface area of drop during ascent) × (average vapor pressure in the height of ascent) × (duration of ascent).

The last is governed jointly by the ascent velocity of the unit prism and the average terminal velocity of the drop during its time of ascent.

If the other factor is frequency of formation of a given drop size by union of two or more drops, this will increase as the cross-section area of the drop, that is, as the square of the diameter. As already shown, the requisite condition for union of drops of equal or nearly equal sizes is not well fulfilled by drops falling in parallel lines, as within the core. It is much better fulfilled for large drops falling through a medium in which the interspersed drops are moving horizontally or at a considerable angle with the path of the large drop. This condition is approximately provided in the peripheral outflow layer.

These considerations indicate that larger drops of peripheral rain from near the core and, to some extent, core rain, will conform to a two-factor frequency equation, such as (1). Peripheral rain occurring in small drops and falling from the outer part of the peripheral ring will conform to a single factor frequency equation

$$f = e^{-kd^m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Both cases are represented by the general equation

$$f = cd^m e^{-kd^n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Landsberger and Neuberger's data represent a case of drop-size distribution for rain (in this case sleet) in a shower with high ascent velocity and precipitation, chiefly from the peripheral belt. Drop-size distribution for core rainfall should also contain an exponential term, not necessarily the same power of diameter d but the other factor or d^2 term should be small or absent in the case of core rainfall. Drop-size distribution data in a proven sample of core precipitation are wanting.

The author believes that hail is formed chiefly by a process analogous to the formation of core rainfall but in vortex rings outside the core and without spreading in the outflow layer. If this is so, then the drop-size distribution for hail should be different from that for peripheral rain and similar to that for core rainfall. Data of frequency of hailstone sizes in India, collected by J. Elliot and analyzed by BROOKS [1944] can be represented by the following equation, derived by the author from another equation given by Brooks

$$F = 1.22\, e^{-1.22d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

F is the frequency of drops equalling or exceeding diameter d in inches. Since the relative frequency F cannot exceed unity, for d = 0.164 inch, (4) gives F = 1.0. The small hailstones considered are of this size.

If F′ is the frequency of hailstones having diameters <d, then

$$F' = 1 - F = 1.22[(1/1.22) - e^{-1.22d^2}] \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The relative frequency f of a specific size d is given by the differential of this equation, or

$$f = df' = [(1.22)^2\, e^{-1.22d}] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

This is a single factor frequency equation representing a simple exhaustion phenomenon.

HOUGHTON and RADFORD [1938] determined the frequency distribution by volume for different drop sizes in clouds and fogs. The resulting frequency curves are slightly skewed but closely resemble the curve of the normal or Gaussian law of error; in other words, these curves

are not greatly different from those of the single term inverse exponential function

$$f = e^{-kd^2}$$

where f is frequency of drop volume, expressed as the product of number of drops and the cube of their diameter. Since raindrops must originate as minute drops or crystals of cloud or fog, this is at least indicative of drop-size distribution in the rain core before breaking up or recombination, and, as far as it goes, confirms the idea that there is a difference of drop-size distribution of core rain and peripheral rain and, in the latter case, a two-factor distribution equation is required to take into account the effect of the merging of drops by collisions.

Dominant drop sizes--DEFANT [1905] called attention to the occurrence of dominant drop sizes in rain and suggested that large drops are the result of successive collisions of drops of an initial size, the drop volumes forming a geometric series with terms 1, 2, 4, 8, ... A tendency toward predominance of particular drop sizes exists in the data of Bentley, Lenard, and, in particular, in the sleet drop sizes observed by Landsberg and Neuberger.

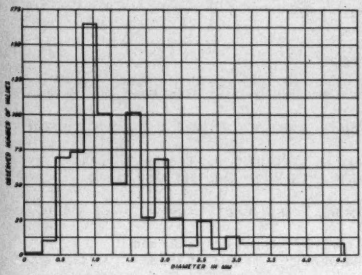

Fig. 5--Size distribution of sleet drops from LANDSBERG and NEUBERGER [1938]

Referring to Figure 5, there is a strong predominance of drops of about 1, 1.5, 2, 2.5, and 3 mm diameter. The corresponding relative volumes per drop are shown in Table 4. In this series a drop of a given diameter has, as a rough approximation, the same volume of two drops 1/2 mm smaller in diameter.

A drop of the critical size in the peripheral belt can overtake one or several drops of approximately the same size. Also it may combine with various smaller drops. Drop diameters increase as the cube roots of the drop volume. For example, increase of diameter by union of a drop of initial diameter d_c with a smaller drop of diameter d' will be

d'/d_c	1.0	0.9	0.8	0.5	0.25	0.10
Relative diameter	1.26	1.24	1.22	1.14	1.08	1.03

The resulting diameters after union of several drops of the same size are

Number	1	2	3	4	5
Diameter	1.0	1.26	1.44	1.59	1.71
Increment of diameter	0.26	0.18	0.15	0.08	

Table 4--Volumes and frequencies of drop sizes

Diameter	Volume per drop (relative)	Frequency	Total volume (relative)
mm			
1.0	1.0	165	165
1.5	3.37	103	347
2.0	8.0	68	544
2.5	15.6	24	374
3.0	27.0	13	351

The final volume of a drop of the critical or nearly critical diameter after falling through the outflow layer will not be precisely an integral multiple of that of the drop corresponding to the number of larger drops combined. A factor controlling this result is the fact that if a drop of critical diameter d_c falls across a stream of smaller drops, the chance of collision with an independent drop is proportional to the square of its diameter.

From Figure 5 the maximum frequency is for dops one mm in diameter; the maximum volume is included in drops two mm in diameter. NEUBERGER [1942] has reviewed the earlier work of Lenard, Mache, Kohler, Defant, Niederdorfer, Hageman, and others on drop-size distribution and the occurrence of predominant drop sizes and gives a bibliography of the subject.

The Defant phenomenon is strongly marked in some drop-size series and little in evidence in other series. This would be true if it occurred chiefly in one of two types of rain, not in the other. Apparently it can occur in both core and peripheral rain but its occurrence is much more frequent and uniform in peripheral rain.

LANDSBERG and NEUBERGER [1938] aptly summarize the result of investigations of the Defant phenomenon, "If liberally interpreted, this can be taken as representing the proportions: 1:2:4:8:16. Other values are, nevertheless, frequently enough represented to show that these proportions may be a predominant feature of drop-size distribution but are by no means a lawfully required order."

It is well established that raindrop sizes and drop-size distribution are highly important factors in relation to soil erosion and they form a powerful tool for the quantitative determination of thunderstorm dimensions and characteristics in rain-intensity distribution. While many more data are needed for final conclusions, data at present available, viewed from various angles, show that observed facts in relation to drop sizes, their statistical and areal distribution in the rain splash, and the occurrence of dominant sizes, are consistent with results which follow from the convection tube model of a thunderstorm.

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THE SAILPLANE AS A METEOROLOGICAL PROBE

August Raspet

Abstract--This paper is written in an effort to introduce a comparatively new research tool to American meteorologists. Of the many instruments available to the research meteorologist, the sailplane or high performance glider is least known. However, immediately after the War the sailplane began to be used in such applications as thunderstorm exploration and studies of airflow over ridges. Since the acceptance of this new tool depends mainly upon the researchers' appreciation of its advantages as well as its limitations, this paper attempts to present some of the characteristics of the sailplane as a probe and as an elevated platform for other meteorological instruments. Certain instruments used in the sailplane are also described since they are not generally known by the meteorologists.

The sailplane used as an instrument--Usually it is thought that the sailplane is merely a carrier for instruments. This is not its principal function. The sailplane is itself an instrument capable of determining the vertical and horizontal components of the airflow in the atmosphere. In order to be classed as a measuring instrument such a device must be capable of calibration. In other words, there must exist a functional relationship between some known parameters and those which are to be measured. For the sailplane, this means that if one flight condition is controlled, another may be inferred from the calibration curve of the sailplane. In Figure 1 are shown calibration curves of different sailplanes. These curves are called velocity polars and represent, at sea level air density, the sinking speed of the sailplane as a function of airspeed.

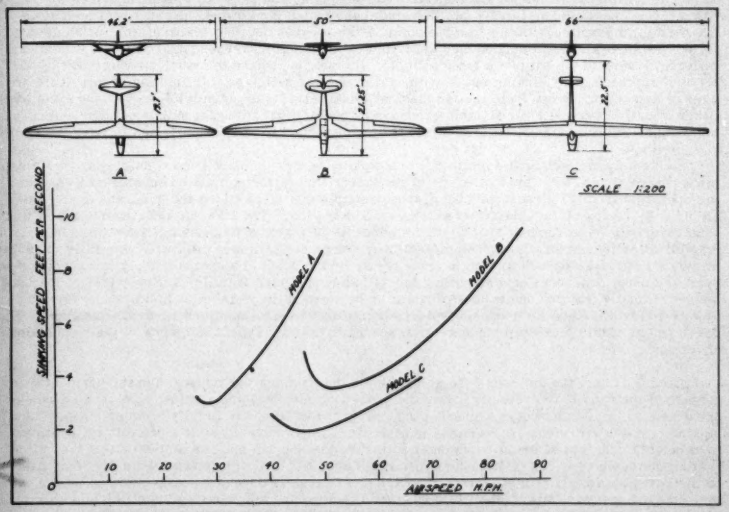

Fig. 1--Velocity polars of three sailplanes

Since the sinking speed in still air of the sailplane is a fixed function of the indicated airspeed of the sailplane, and is a single-valued function of airspeed, it is evident that the sailplane

may be used to measure the vertical motions of the air. It is merely necessary to determine the vertical velocity of the sailplane. Then,

$$W = \dot{Z} - V_S\sqrt{\rho_0/\rho}$$

Where W is the vertical velocity of the air motion, $\dot{Z}$ is the vertical velocity of the sailplane, V_S is the sailplane's sinking speed read from the velocity polar, and ρ and ρ_0 are the air densities at flight altitude and sea level, respectively. The vertical velocity of the sailplane may be determined from radar or theodolite tracking or by means of a low lag variometer on the sailplane. This instrument will be described in more detail later in this paper.

The reason that the vertical component of air flow can be measured so readily lies in the fact that the velocity polar of a sailplane is uniquely determined since it depends only upon the rate of loss of energy as a function of forward speed. If another parameter such as thrust from an engine is introduced, this relation can no longer be retained unless the thrust can be held constant. So far, sufficiently accurate thrust meters have not been developed. In other words, the powered aircraft cannot at present be used for accurately delineating small vertical motions of the air mass.

For the determination of the horizontal component U of the wind in the flight plane, the sailplane's ground speed $\dot{X}$ as well as the indicated airspeed of the sailplane V_i are required

$$U = \dot{X} - V_i\sqrt{\rho_0/\rho}$$

where ρ and ρ_0 are air densities defined as above. The ground speed of the sailplane may be obtained from radar or theodolite tracking or from drift sight observation from the sailplane. Where the wind is not in the direction of the flight plane only the component in the flight plane will be determined by this method. A more general technique for determining the vector horizontal wind will be described in a subsequent section.

Yet another property of the sailplane is intrinsically contained in the velocity polar. Since it is possible to increase the forward speed of the sailplane, and know its sinking speed at any forward speed, the sailplane can fly into the wind, penetrating far upwind. (Evidently, penetration of the wind is impossible with the free balloon.) After progressing into the wind, the sailplane can fly downwind at a lower airspeed thus describing a series of traverses parallel to the wind and at different levels as the sailplane loses altitude. (In the case where the vertical component of the air motion exceeds the sinking speed of the sailplane, the sailplane will actually climb. This process of extracting energy from the air mass and converting it to potential energy in the form of altitude is called soaring.) By suitable ground control the flight path of a sailplane may be accurately controlled. A discussion of various methods of ground control will be contained in later paragraphs.

So far only the technical aspects of the sailplane as a probe have been considered. For a complete description of this new tool, some of its operational features must be enumerated. Assuming operation from an airport as a base, it is a simple matter to attach the sailplane to any small airplane by means of suitable safety releases and a towline. The take-off and climb to the altitude where exploration is desired is straight-forward. It may happen that landing back at the base is not feasible after the exploration is completed. Any competent sailplane pilot will have little difficulty finding a field large enough to land in since the sailplane lands at a comparatively low speed. However, the usual procedure of dismantling the sailplane to return it to its base on a trailer may not be operationally feasible due to lack of roads or because of the time lost. In this case, there is now available a method for launching gliders by means of a non-stop pick-up by the towplane. The development of this pick-up technique for research sailplanes should add much to their operational efficiency.

Since the basis for the use of the sailplane for determining the vertical and the horizontal components of the wind is the velocity polar, the procedure for obtaining a velocity polar shall now be presented. The velocity polar expresses a relation at sea level air density between airspeed and sinking speed in air having no vertical motion. It is imperative then, if a reliable calibration is to be obtained, that some pains be taken to insure that the air mass is stable or that the calibrating instruments used are immune to air mass motion. Little progress has so far been made on the latter approach. Flight testing of sailplanes is usually done in the early hours of the morning while the air mass is still stable. Temperature readings are taken during the climb (under tow) to determine the stability of the air mass and to permit density corrections to be made. When sufficient altitude is attained, the sailplane pilot releases from the towplane, stabilizes his craft at a fixed airspeed in straight flight. He radios to a ground recorder his altitude at fixed intervals. A plot of the altitude versus time permits the determination of the indicated sinking speed. The linearity of the plot is a test of the stability of the air and the skill of the pilot. If the plot is

linear and if the lapse rate shows stability over large areas, the data may be taken as reliable. A series at various airspeeds of such data reduced to sea level air density yields the velocity polar. Too much emphasis cannot be placed on this phase of the sailplane's calibration.

The calibration of the airspeed measuring system is also required since the pitot-static airspeed tube when mounted on any aerodynamic shape, such as the fuselage, has a position error due to the acceleration of the air around that aerodynamic shape. For this calibration a static sonde is usually lowered a considerable distance below the sailplane into undisturbed air. Connected to the total pressure head on the sailplane and the static sonde is a standardized airspeed meter. Comparison of the instrument on the flight panel and the standard permits corrections to be determined for the flight instrument.

Having a series of velocity polars for various sailplanes, one must consider what properties a meteorological research sailplane must possess in order to yield highest precision and offer best overall efficiency. In Figure 1 are velocity polars of three sailplanes and drawings showing their lines. Model A has a relatively low minimum sinking speed at a rather low forward speed. On the other hand, Model B has a higher minimum sinking speed than A at a considerably higher indicated airspeed. Furthermore, it will be seen that where Model B has its minimum sinking speed, Model A has a sinking speed nearly twice that value. In other words, if Model A were required to penetrate a wind of moderate velocity, it would do so at a considerable loss in altitude. Fewer traverses in an exploration would be obtained on each flight. However, if small structures in a light wind are to be delineated, the slower speed of Model A is an advantage. Examination of the velocity polar for Model C shows it to possess both low sinking speed at low airspeed and good penetration. Such a sailplane is aerodynamically best suited to exploration of the air mass. However, Model C is a large sailplane and may require a larger ground handling crew than either Model A or Model B.

Most important in a meteorological research sailplane is space in which to install special recording instruments, oxygen breathing equipment, radio communicating sets, and insulation and heating for the pilot. Ease of dismantling is of prime importance where flexibility of operation is demanded.

Instrumentation and equipment for the meteorological research sailplane--The demands on the instrumentation for sailplanes are much more severe than those for powered aircraft. Since the source of sustaining power comes from the atmosphere, it is extremely important that the sailplane be so flown that its losses are held at a minimum. This demand alone requires an airspeed indicator installation which is sensitive and has a low lag and which is furthermore immune to icing without requiring electrical heating. In order to maintain alignment of the sailplane's axis with the flight path (a condition for minimum energy loss) in the horizontal plane, a skid vane is used where highest precision is demanded. Correct alignment to within two degrees is possible with a statically balanced skid vane (see Fig. 2). For controlling the turning rate, an electric turn meter especially adjusted for sailplanes is required. Turning rates are usually much higher than those covered by aircraft instruments.

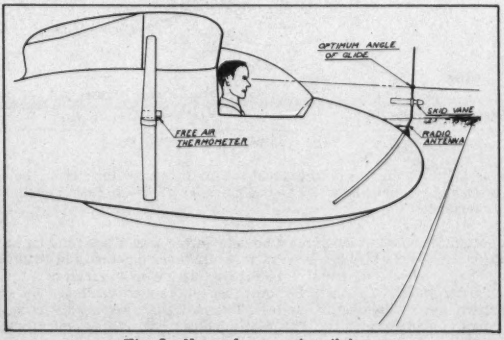

Fig. 2--Nose of research sailplane

An important consideration for any instrument used for atmospheric microstructure studies is its resolving power for those structures. The resolving power of a sailplane and an instrument is defined as the smallest horizontal dimension of an atmospheric structure which can be detected by that particular instrument when carried by the sailplane at an indicated airspeed V_i. Thus

$$R = \lambda V_i$$

in which R is the resolving power, and λ is the lag of the detecting instrument. From this consideration it is apparent why an airplane equipped with a standard airplane rate of climb indicator would be unable to detect small vertical convection cells. On the other hand, a sailplane cruising at 15 m/sec, equipped with a variometer of one sec lag, would be able to delineate a structure as small as 15 m across. Figure 3 shows the resolution of vertical convection as obtained from two

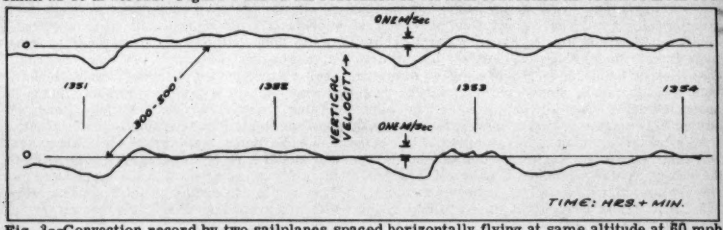

Fig. 3--Convection record by two sailplanes spaced horizontally flying at same altitude at 60 mph

sailplanes flying side by side at 60 mph.

It may be well to describe the rate of climb variometer which is currently used in sailplanes for meteorological research. The general principle of the variometer lies in the measurement of the flow from a thermally insulated container as the air expands in the container due to a reduction of outside pressure as the craft climbs. The essence of this instrument is the vane flow meter used to measure flow (see Fig. 4). Because a very small energy is required to deflect this

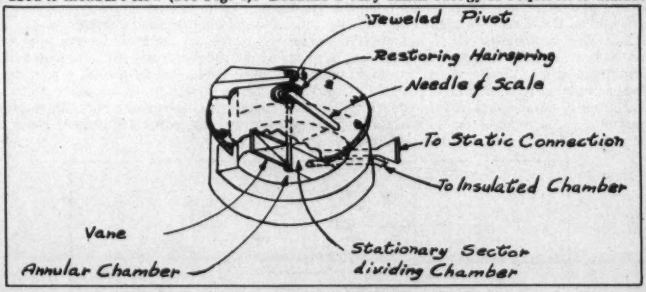

Fig. 4--Vane type variometer after Horn

instrument, its lag is small. It will be noted that the air flow acts directly on the vane which is suspended on jewels and restored by a low torque hairspring. These instruments are at present made only in Switzerland.

Another important parameter which must be determined with a low time lag is the free-air temperature. Here again, the classical aircraft free-air thermometer is of little use because it has a long lag and has too low a sensitivity. In Figure 5 is shown a circuit of a low lag thermomete capable of a sensitivity of 0.01°C. It will be noted that this is a conventional Wheatstone bridge circuit with the thermometer element in one leg. Two indicators are used, one for the pilot and one which is recorded photographically. The pilot's indicator is used principally to indicate to the pilot that a change in the decade resistance is required.

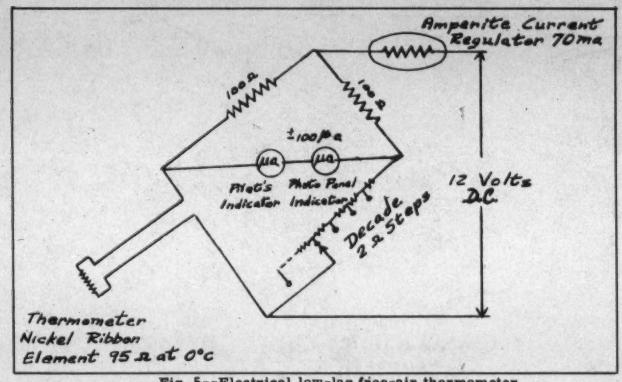

Fig. 5--Electrical low-lag free-air thermometer

The element of this thermometer consists of a nickel strip 0.0005 inches × 0.010 inches. This strip is wound on a balsa former made of balsa sheets on edge. The former in the shape of a hexagonal pyramid is suspended inside an aluminum shield by light threads. A calibration of this instrument is shown in Figure 6.

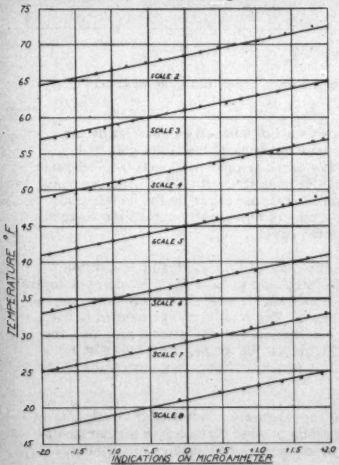

Fig. 6--Calibration of resistance thermometer for low-lag free-air measurements

It would be possible to wind the nickel around a balsa former covered with gauze which could be kept moist. Thus a wet bulb reading would be available, though with a larger lag than that of the dry bulb.

A VHF transmitter is also carried in the research sailplane, Model A of Figure 1, the antenna of which can be seen in Figure 2 supporting the skid vane and the optimum glide angle indicator. A small superregenerative receiver complements the transmitter in order to be able to instruct the pilot from the ground. A small storage battery supplies power to the radio equipment and to the cine camera which records at one frame per sec the various instruments indicating physical properties of the atmosphere. The battery furnishes enough power to supply the camera, radios, and electric thermometer for one hour. This is also the time limit of the film supply for the camera.

In spite of the completeness of the instrumentation for this particular sailplane, the total weight of the additional equipment is less than 20 pounds. This is the limit, however, for this particular craft. It must be emphasized that for certain researches the instrumentation may be heavier, in which case a large sailplane must be selected. For the sailplanes participating in the Thunderstorm Research in 1946, the equipment weighed well over 200 pounds.

Ground equipment for tracking the sailplane will depend on the measurements to be made. For a ridge flow exploration, a specially modified theodolite is being used (see Fig. 7). The theodolite was equipped with a high intensity concentrated arc lamp and a projector lens. These were mounted on the end opposite the theodolite objective where the mass balance is attached. With the projector it is possible to follow the point of light across a tracing paper on a vertical

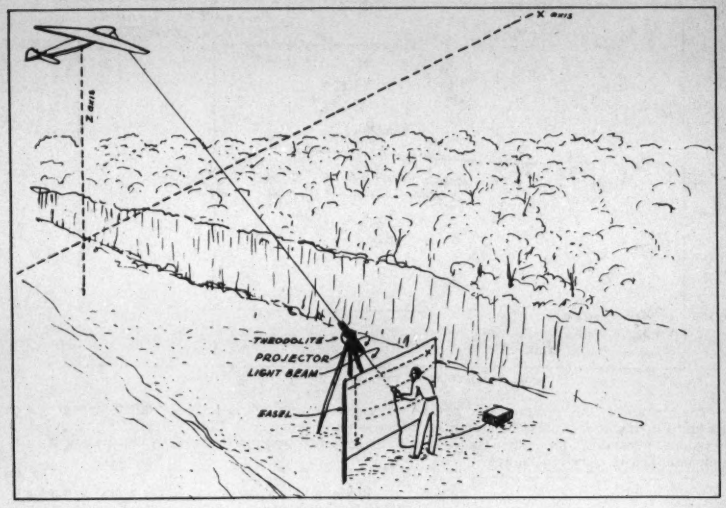

Fig. 7--Mapping scheme

easel in broad daylight. This theodolite was also equipped with a crank for ease of tracking and a lower power ocular.

The theodolite technique with which this instrument was used is based on restricting the sailplane to fly in a fixed vertical plane. By so doing, a true mapping of the flight path of the sailplane is obtained on the easel if the flight plane and the easel are parallel. Another operator is required, of course, to follow the projected light spot. He does this with a pen which is connected to a timer so that every second an ink dot is deposited on the tracing paper on the easel. This method of recording displacements and thus arriving at a map is universally applicable to such tracking problems as can be reduced to the two-dimensional case.

For defining the vertical plane, it is well to relieve the pilot of this burden of navigation. Early efforts were made in the ridge study now under investigation to have the pilot determine his correction for drift and to hold a fixed heading during a traverse. If land marks are not conspicuous, a large source of error can develop from this technique. The ideal arrangement is to use an observer on the ground in the flight plane. He tracks the sailplane with the gimbal axis of a theodolite perpendicular to the vertical plane in which the flight is to be made. He follows with the elevation knob and radios corrections to the pilot. In this manner, continuous corrections of heading are made.

The above process has interesting ramifications. If the magnetic heading of the sailplane is recorded continuously as the traverse is flown, the variations in wind direction in the horizontal plane are determinable as well as the magnitude of the wind vector. For studies of turbulence aloft, such an approach should prove useful.

In the realm of future development, it appears entirely feasible that microturbulence can be determined from either oscillations in airspeed [TOLEFSON, 1945] or from oscillations of a critically damped angle of attack vane or a skid vane. The two orthogonal components of the turbulence can be determined from a combination of the latter instruments. An example of large turbulence, essentially a vortex with a vertical axis, can be seen from Figure 8 which is a section of a time history of a flight made into a thunderstorm. The airspeed is seen to fluctuate harmonically from 50 to 90 mph at a frequency equal to the turning velocity of the sailplane. It will be seen

that the airspeed accelerated from 50 to 90 mph in less than four sec. Such accelerations of the sailplane are impossible even in a vertical dive. It must be concluded that the sailplane was crossing a vortex each time he completed a turn.

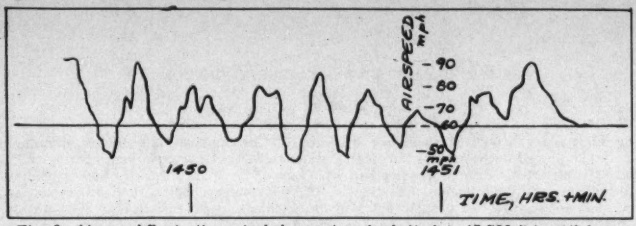

Fig. 8--Airspeed fluctuations; turbulence at peak of climb to 17,700 ft in sailplane; thunderstorm of July 3, 1946

Another research in which the sailplane may be able to contribute lies in the field of diffusion studies. If a sailplane were fitted with an ion counter, it would be possible to use a radioactive gas as a tracer and to make traverses through the diffused gas at various levels recording the ion count along each traverse. The particular property which the sailplane offers here is its smooth passage through the air. The mixing introduced by the sailplane would be very slight at large distances from the tracer source.

With a sailplane of wood construction, measurements of the electrical field within clouds is possible without essential error caused by a charge on the craft. Such explorations have been made in Germany attaining results which appear lower than those given by GUNN [1948]. Gunn, in fact, states that the fields determined by himself were an upper limit rather than an absolute value.

Much more development is necessary before the sailplane's applications are exhausted. The elegance which radio telemetry would offer in presenting an immediate picture to the meteorologist cannot be overemphasized. By this means, he could observe the field point as well as observe various physical properties of the air at that point and could, if he wished, direct the pilot by radio to interesting areas. In clouds, radar tracking would be needed in order to relate the coordinates of the sailplane to those of the cloud. The physical parameters as a time history for later analysis should, of course, be recorded.

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THE MACELWANE-SPRENGNETHER MAGNETOMETER

J. B. Macelwane and W. F. Sprengnether, Jr.

For many years, a need has been felt by teachers of geophysics for a field magnetometer which could be placed in the hands of beginning students without too great risk of irreparable damage. It is obvious to anyone who has had experience with undergraduates that appreciation of delicate instruments is not inborn or instinctive. Only by patient instruction and gradual experience do students acquire that respect for delicate mechanisms, that knowledge of slight tolerances, that feeling for and skill in making fine adjustments that are a sine qua non in the care and manipulation of a precision instrument.

It is not only a wasteful practice, but very bad pedagogy to place an instrument of high precision in the hands of a beginner who has no idea of its limitations and how easily it may be thrown out of adjustment. For example, the authors know of a case in which large, high-precision calipers were made available to unskilled workers in a war plant and were used as hooks to drag heavy boxes across the floor. They had no idea they were ruining the calipers. So it is with magnetometers. A beginning student neither knows, nor is he in sympathy with, the gentleness that must be exercised in handling a precision magnetometer of the Schmidt balance type to prevent change of the scale by jarring, or even to avoid such damage to the knife edges as will necessitate return of the instrument to the factory for repair and recalibration.

More advanced students who come into a course in geophysics with experience and skill in the use of sensitive equipment are inclined to approach an instrument as delicate and costly as the standard precision magnetometer with a degree of awe which will make him hesitant to manipulate or adjust it. While this salutary respect is fully justified from the standpoint of the instrument, it impedes the learning process.

Fig. 1--Schmidt balance magnetometer

A student magnetometer is needed which can be used to train the student in precision habits. The requirements for such an instrument are: (1) Sufficient sensitivity to illustrate the use of the Schmidt balance in mapping; (2) rugged construction to withstand ordinary student handling; (3) ease of repair in case of damage; (4) ease of adjustment in the field over a fairly wide range; and (5) moderate cost so that numbers can be provided.

Several years ago a horizontal and a vertical component Schmidt balance magnetometer (see Fig. 1) of very simple type were designed and built by the authors. These have been used through the years with sufficiently satisfactory results. The attainable sensitivity was about 75 g per scale division and could be varied over a considerable range, repairs were easily made, the instruments were very light and easily carried, and their principle of operation was obvious to the student. However, they had certain defects. The control was somewhat erratic, the clamping and release mechanism was not positive in its action, the orienting arrangement was not entirely satisfactory, and the tripod was not sufficiently rigid. The students could obtain consistent results with these instruments but often complained about their shortcomings.

Fig. 2--New student magnetometer in use

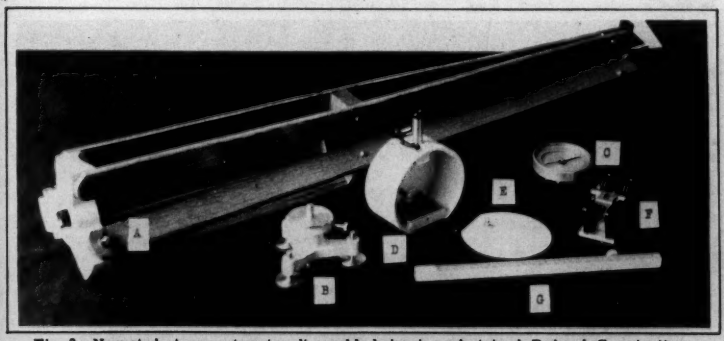

Fig. 3--New student magnetometer dissembled showing: A, tripod; B, head; C, orienting compass; D, case with microscopic and crossed levels; E, swiveling or removable case door allowing all adjustments of the needle system to be placed in view of the microscope; F, magnetic needle system: G, reversible auxiliary magnet holder, scale, and indicator

The new student magnetometer (see Fig. 2) has been designed with a view to rigidity, positiveness of control and release, and extreme ease of adjustment. At the same time the simplicity and ease of repair of the older type has been retained in the new magnetometer. Its cost will be within the range of ordinary engineering instruments. Figure 3 shows the new student magnetometer dissembled. It can be dismantled for demonstration and reassembled in a few minutes.

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LONG-RANGE FLIGHT BY SINGLE MAGNETIC HEADING

Irving I. Gringorten

Abstract--The purpose of this paper is to describe a system which will enable a navigator to plan a long-range flight easily which will require only one heading of the aircraft by his magnetic compass. Such a system will make possible automatic flying or the flight of pilotless aircraft. The paper shows how to find the track that the aircraft should make good, giving one example of a cross-country flight near the 10,000-ft level.

Introduction

In recent years long-range aerial navigation has sought for an application of meteorology to reduce flying time and yet to simplify the navigator's duties while in flight. There has been a trend, therefore, toward the adoption of single heading flight, in which the heading of the aircraft remains unaltered from point of departure to destination [LAMBACH, MANSFIELD, and BOLTON, 1945; NAVY DEPARTMENT, 1946; GRINGORTEN, 1947 a and b, 1948]. In the absence of winds, this heading reduces to the constant bearing between the two airports. In the presence of winds, the heading is corrected by an average drift angle which is generally small over a long range. The forward speed of the aircraft is not diminished by excessive crabbing, so that this flight procedure usually does lessen flying time. In addition, the system allows for flight over regions where the wind field is relatively unknown. Unless otherwise specified, the heading is "true" heading, measured with respect to geographic north.

Single true heading, however, does not serve for automatic flying, or the flight of pilotless aircraft. A navigator still must be on the alert to keep his aircraft on its heading which corresponds to a continually changing reading of the magnetic compass. For this reason the present paper is devoted to the derivation of a formula for the single magnetic heading, and to the plotting of the expected track.

There are two factors that require compensation to make single magnetic heading possible. The first is the magnetic variation which differs from one place to another. The second is wind force and direction which likewise varies considerably in space. In the following sections the formulas and procedures are developed for finding the heading and the expected track of an aircraft that is to be flown with a single reading of the magnetic compass. It is assumed that the aircraft flies at constant air speed and is limited to a constant-pressure surface which is a constant indicated altitude. The surface is nearly spherical, like the Earth, and is assumed as such.

Fundamental relations

Let the spherical surface of the Earth, as illustrated in Figure 1, be projected onto a conformal chart, so that all angular measurements will remain unaltered in the projection, as in Figure 2 [DEETZ, 1934]. This chart will be a Mercator or a Lambert conformal or a polar stereographic, the projections normally used for weather charts. The scale factor S is a function of latitude ϕ only: $S = 1/(\cos\phi)^{1-p}(1+\sin\phi)^{p}$ where $p = 0$ for the Mercator chart, $p = \sin(\alpha+\beta)/2$ for the Lambert conformal chart with standard parallels α and β, and $p = 1$ for the polar stereographic projection. Because of conformality, any short distance on the chart δs_m will be S times the corresponding distance on the sphere δs.

$$\delta s_m = S\,\delta s \qquad \delta x_m = S\,\delta x \qquad \delta y_m = S\,\delta y \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

Suppose the heading of the aircraft makes an angle χ with the X-direction. Then the ground-speed of the aircraft $\underline{G}(\dot{x}, \dot{y})$ is equal to the vector sum of the airspeed $\underline{c}$ (c cos χ, c sin χ) and the wind $\underline{V}(u, v)$. Or

$$\dot{x} = c\cos\chi + u \qquad \dot{y} = c\sin\chi + v \qquad \ldots\ldots\ldots\ldots\ldots (2)$$

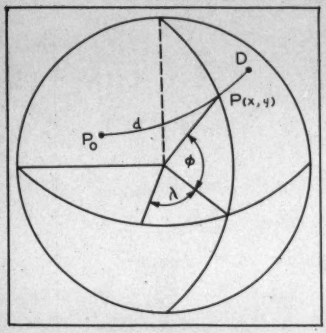

Fig. 1--Diagram of a sphere, showing point of departure P_0, destination D, any point P with latitude and longitude (ϕ, λ), on the track of length d

In Figure 3, the heading of the aircraft with respect to the X_m- axis is represented by ζ and the heading with respect to magnetic east is η. The angle between the two axes is ∂, which becomes ∂_T, the magnetic variation, when the Mercator chart is used. Thus,

$$\zeta = \eta + \partial \quad \ldots\ldots\ldots\ldots (3)$$

For single magnetic heading, η is constant.

To find the single magnetic heading

Referring to the angle between the heading of the aircraft and the wind direction as α (see Fig. 3), it can be shown from relations (2) and (3)

$$\cos \eta\, dy - \sin \eta\, dx = (c + V \cos \alpha) \sin \partial\, dt$$

$$+ V \sin \alpha \cos \partial\, dt \quad \ldots\ldots\ldots (4)$$

where dt is an element of time, and dx, dy are coordinates of the infinitesimal distance ds. Let β be the drift angle, as shown in Figure 4. Then, from (4) and (1)

$$\cos \eta\, dy_m - \sin \eta\, dx_m = \sin (\partial + \beta)\, ds_m \quad \ldots\ldots\ldots\ldots\ldots (4a)$$

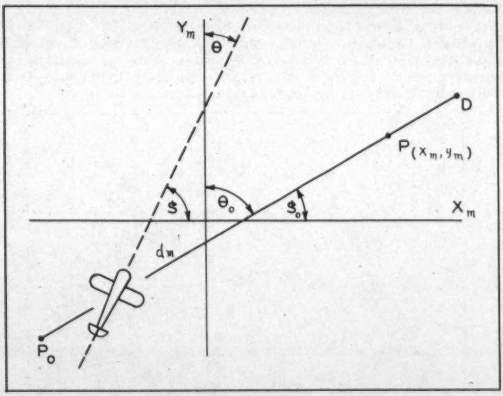

Fig. 2--Diagram of a conformal chart, showing rectangular axes X_m, Y_m, point of departure P_0, destination D, any point P with coordinates (x_m, y_m) on the striaght-line track of map-length d_m

Integrate from P_0 to D (points of departure and destination)

$$\cos \eta (y_D - y_0) - \sin \eta (x_D - x_0) = \int_{P_0}^{D} \sin (\partial + \beta) ds_m \quad \ldots\ldots\ldots\ldots (5)$$

But ($x_D - x_0$ and ($y_D - y_0$) are the components of the straight-line distance d_m of the chart (see Fig. 2). If ζ_0 is the angle that the line P_0D makes with the X_m-axis, then, from (5)

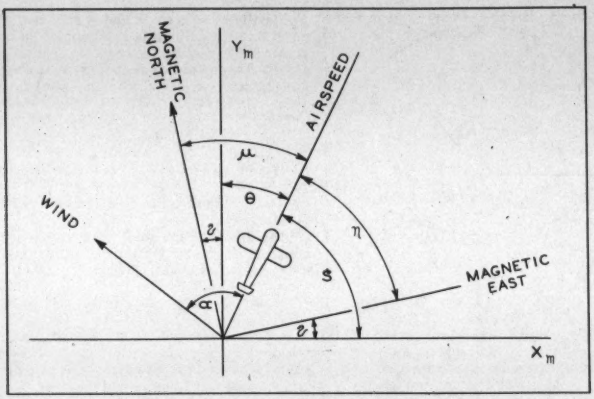

Fig. 3--The relation between the various angles on the chart

$$\sin(\zeta_0 - \eta) = 1/d_m \int_{P_0}^{D} \sin(\partial + \beta) ds_m \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

At this stage we must depart from the rigors of mathematics and resort to approximations and generalizations because the integral on the right of (6) is not completely determinable. First of all, the path of the aircraft from P_0 to D should be known before the integration is performed, whereas to find this very path is part of our problem. Secondly, the drift angle β is not known, although the average drift angle $\bar{\beta}$ may be closely approximated.

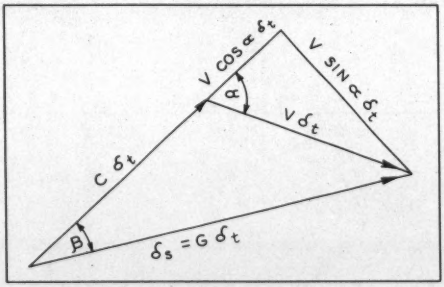

Fig. 4--The relation between ground distance δs, air distance $c\,\delta t$, and wind motion for a small increment of time δt

In general, the actual path of the aircraft from P_0 to D will be sufficiently adjacent to the straight line P_0D of Figure 2, so as to allow us to perform the integration over the straight line P_0D as a first approximation. From (6), therefore, $\sin M = \sin z$ where $M = \zeta_0 - \eta$; $z = \partial + \beta$, expanding by Taylor's Theorem, $M - M^3/3 + M^5/5! + \ldots = 1/N\Sigma z - 1/3!\, N\Sigma z^3 + 1/5!\, N\Sigma z^5 + \ldots$. But, neither M nor z is greater than $\pm 25°$ or ± 0.44 radians. Hence, by neglecting terms of order $M^3/3!$ and higher, the error introduced is about three per cent or less. Moreover, when the terms on the left and right are neglected in pairs, the error introduced becomes even smaller. Assume, therefore, that $M = 1/N\Sigma z$, or $(\zeta_0 - \eta) = \bar{\partial} + \bar{\beta}$.

If, now, χ_0 is replaced by $\pi/2 - \theta_0$, and η is replaced by $\pi/2 - \mu$ then $\mu = \theta_0 + \bar{\delta} + \bar{\beta}$. If the projection is a Mercator projection, then

$$\mu = \theta_0 + \bar{\delta}_T + \bar{\beta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where μ is the single reading on the magnetic compass (see Fig. 3), θ_0 is the true bearing of the rhumb line from P_0 to D (see Fig. 2), $\bar{\delta}_T$ is the average magnetic variation from true north (positive for variation west), $\bar{\beta}$ is the average drift-correction angle.

Case 1: The no-wind condition--When the winds are everywhere zero, $\bar{\beta} = 0$, so that (7) reduces to $\mu_0 = \theta_0 + \bar{\delta}_T$. In order to find the single-magnetic no-wind heading, μ_0 it is necessary to find the true bearing θ_0 from a Mercator chart or formula, $\cot \theta_0 = 131.929\,[\log \tan (\pi/4 + \phi_D/2) - \log \tan (\pi/4 + \phi_0/2)]/(\lambda_D - \lambda_0)$, where (ϕ_0, λ_0) are the latitude and longitude of point of departure (degree and tenths), (ϕ_D, λ_D) are the latitude and longitude of the destination.

$$\sin \bar{\delta}_T = 1/d_m \int_{P_0}^{D} \sin \delta_T \, ds_m = 1/d_m \sum_{P_0}^{D} \sin \delta_T \, \delta s_m$$

where the summation can be performed by dividing the straight-line track P_0D into segments of length, say, 200 nm. The total distance d_m should be verified by the formula $d_m = 60(\lambda_D - \lambda_0)/\sin \theta_0$. All distances should be measured with the equatorial scale of the chart.

Case 2: The variable-wind condition--From (7) it is seen that the single magnetic heading $\mu = \mu_0 + \bar{\beta}$ where μ_0 is the same as under Case 1, and $\bar{\beta}$ is the average drift-correction angle. Being generally small, $\bar{\beta}$ can be found over the straight-line track by the formula

$$\sin \bar{\beta} = 1/d_m \int_{P_0}^{D} \sin \beta \, ds_m$$

If the winds are geostrophic this formula reduces to $\sin \bar{\beta} = 21.5\,(Z_D - Z_0)/cd \sin \bar{\phi}$ [NAVY, 1946], where d should be the distance along the single magnetic track but can be approximated by the rhumb-line distance on the sphere, $d = 60\,(\phi_D - \phi_0)/\cos \theta_0$ (nm). Z_D is the height of the constant pressure level over the destination (a forecasted height), Z_0 is the height over the point of departure, c is the airspeed of the airplane in knots, $\bar{\phi}$ is the mid-latitude of the rhumb line P_0D.

To find any point on the expected track

If both sides of (4a) are integrated from P_0 to any point P, the equation becomes

$$\cos \eta \,(y_m - y_0) - \sin \eta \,(x_m - x_0) = \int_{P_0}^{P} \sin (\delta + \beta) ds_m \quad \ldots\ldots\ldots\ldots (8)$$

This is the equation of a straight line whose angle with the X_m-axis is η and whose distance from P_0 is $\int_{P_0}^{P} \sin (\delta + \beta) ds_m$, as in Figure 5. This suggests ways and means of finding points, like P, of the single-magnetic track.

Case 1: Winds zero everywhere (that is, $\beta \equiv 0$)--In this case the integral on the right-hand side of (8) becomes

$$\int_{P_0}^{P} \sin \delta \, ds_m$$

If this integral is evaluated from P_0 to any point P'' along the straight line P_0D, as in Figure 5, it will be a sufficiently close approximation. Thus, P will lie at the intersection of the circle through P'' with center at P_0 and the straight line of slope $\tan \eta$ and distance

$$\int_{P_0}^{P''} \sin \delta \, ds_m$$

from P_0.

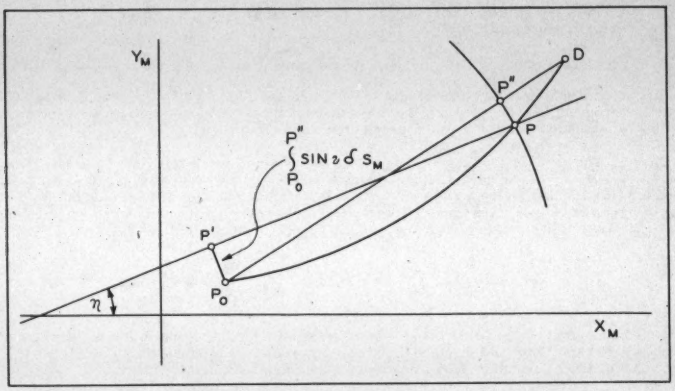

Fig. 5--Method of finding a point P on the expected no-wind single-magnetic-heading track from P_0 to D

Similarly, any number of points like P may be found along the expected track.

Case 2: A steady wind from a constant magnetic direction (that is, β is constant)--In this case, the track of the airplane will be identical with the track for the no-wind condition.

It serves our purpose to separate the influence of the wind from the influence of the magnetic variation, which can be done in an approximate manner, as illustrated in Figure 6. The line P_0PD represents the single-magnetic-heading track in the steady-wind condition for which the drift-correction angle is β. If the aircraft were flown with the corrected heading in the absence of wind, it would have flown over track $P_0P'D'$. Thus, the distances P'P and D'D represent the drift of the aircraft due to the uniform wind.

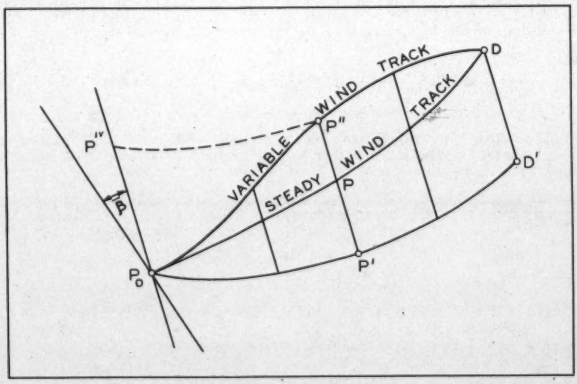

Fig. 6--The relation of the steady-wind track and the variable-wind track to the air path $P_0P'D'$

Case 3: Variable winds--When the winds vary, but the overall drift-correction angle is $\bar{\beta}$, then the aircraft will be headed in the same constant magnetic direction as if the wind were steady and causing drift angle $\bar{\beta}$. For this reason the line $P_0P'D'$ of Figure 6 may be treated as the base line from which the drift of the aircraft $P'P''$ may be plotted. The length of the line $P'P''$ is given by the conventional formula for drift $P'P'' = 21.5\ (Z - Z_0)/c \sin \bar{\phi}$ [LAMBACH, MANSFIELD, and BOLTON, 1945] where Z is the height of the constant-pressure surface at P'', and Z_0, c, and ϕ are defined as above. This suggests a method for finding the expected track, as illustrated in Figure 6.

Make $P_0P^{iv} = 21.5\ (Z - Z_0)/c \sin \bar{\phi}$, where $(Z - Z_0)$ is given one of the successive values 0 ft, 200 ft, 400 ft, and other values. Trace the curve through P^{iv} that parallels the base curve $P_0P'D'$, letting it cut the Z-contour at the desired point P''. (The Z-contours are not shown on Figure 6 to avoid confusing the figure with too many lines.) Similarly, any number of points like P'' may be found along the single-magnetic-heading track.

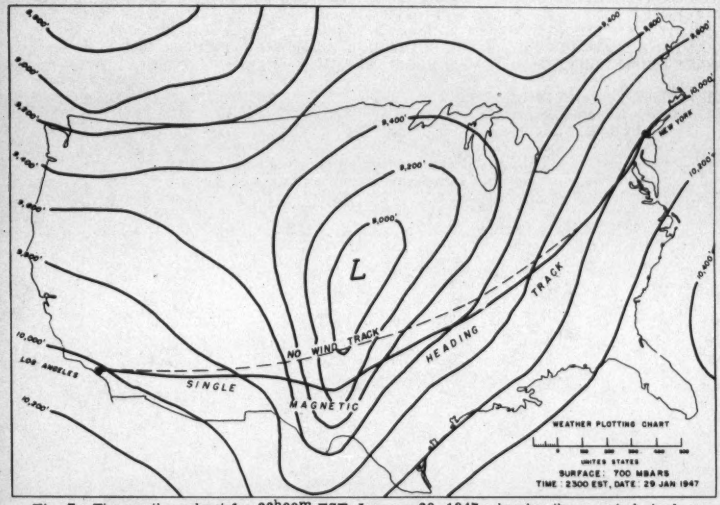

Fig. 7--The weather chart for 23^h00^m EST, January 29, 1947, showing the no-wind single magnetic track and the single magnetic track for the 700-mb surface pattern

Example--Figure 7 shows a weather chart of the United States on which are plotted the no-wind single-magnetic heading track and the single-magnetic track for the 500-mb pressure pattern at 23^h00^m EST, January 29, 1947.

Summary

The actual single magnetic heading, μ, between the airports is given by the formula

$$\mu = \theta_0 + \bar{\delta}_T + \bar{\beta}$$

where θ_0 is the rhumb-line bearing between point of departure and destination, $\bar{\delta}_T$ is the average magnetic variation which is a constant for the given airports and determinable from the formula

$$\sin \bar{\delta}_T = 1/d_m \int_{P_0}^{D} \sin \delta_T \, ds_m$$

$\bar{\beta}$ is the average drift-correction angle determined by formula $\sin \bar{\beta} = (21.5)(Z_D - Z_0)/c.d \sin \bar{\phi}$. This makes it possible to find the magnetic heading in about one minute by means of a special computer or nomogram.

It is possible to plot the expected track, and it has been plotted, in about ten minutes. While the explicit instructions for plotting this track are not given in the above report, they can be readily outlined.

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THE REFLECTION OF DIFFUSE RADIATION BY THE SEA SURFACE

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Abstract--Measurements of the fraction of the solar radiation passing through stratus cloud reflected by the sea surface led to the conclusion that the radiation is not completely diffuse. The average albedo was 10.5 per cent with values varying with cloud thickness and solar elevation. The indication is that for completely diffuse radiation Schmidt's theoretical value of 17 per cent would apply.

During the summer of 1945 the University of California, as part of an investigation carried out under contract with the United States Weather Bureau, took a series of observations of the reflection and transmission of solar radiation by stratus cloud. The results of those observations will be reported shortly. The present paper concerns itself with a by-product of that study, namely, the observations of the reflection by the sea of the energy which passed through the clouds.

Knowledge of the reflectivity of the sea surface is of fundamental importance for heat-balance studies, both of the atmosphere and the ocean. In order to evaluate the amount of solar energy absorbed by the sea, it is necessary to know not only the amount incident on the surface, but to know also what portion of that is returned, unchanged, by reflection at the surface and by scattering from bubbles and suspended particles immediately below it.

Previous studies of the reflectivity of daylight by the sea surface are principally the theoretical evaluations of ZENKER [1888, p. 54] and SCHMIDT [1915], and the measurements of POWELL and CLARKE [1936]. For sunlight, Schmidt, correcting some errors by Zenker, gives the values in line 1 of Table 1 for the variation of reflectivity with solar altitude.

Table 1--Percentage of radiation reflected by a smooth water surface

Line	Type of radiation	Solar altitude					
		10°	20°	30°	40°	50°	60-90°
		pct	pct	pct	pct	pct	pct
1	Solar	35	13	6	3	2	2
2	Solar and sky (Schmidt)	28	14	8	6	5	4
3	Solar and sky (Sverdrup)	25	12	6	4	3	3

These values do not include the "skylight," the illumination received at the surface due to scattering by the atmosphere. For diffuse radiation, such as that from the sky or transmitted by sufficiently thick clouds, Schmidt computed a reflectivity of 17 per cent. Using this value for sky radiation, he arrived at the values in line 2 for the reflectivity of the total radiation on clear days.

Powell and Clarke's measurements gave values of about three to four per cent for clear days with high sun and smooth sea, and not exceeding nine per cent for solar altitudes greater than 30°. For cloudy weather (diffuse radiation) they found an average value of about eight per cent. SVERDRUP, JOHNSON, and FLEMING [1942, p. 104], using Schmidt's values for solar radiation and Powell and Clarke's value of eight per cent for cloudy days as representative of diffuse radiation, obtained the values for reflectivity of total sun and sky radiation given in line 3 of Table 1. These correspond quite well to Powell and Clarke's data for clear days.

Observational technique and errors--Two Eppley pyrheliometers were mounted on a blimp (non-rigid lighter-than-air ship) furnished by the United States Navy. One instrument, facing upward, measured the total energy in the range 0.3 microns to 2.5 microns falling on a horizontal surface from above. The other measured the energy in these wave lengths passing upward from below, per unit horizontal surface. The ratio of the readings of the latter to the former when the blimp is below the base of the clouds gives the reflectivity of the sea surface, slightly augmented by the scattering by the particles in the air between it and the lower instrument.

In addition to the effect of the scattered light just referred to, there are several other sources of error which enter. Firstly, it was impossible to have the lower pyrheliometer mounted below all parts of the ship. The radar dome extended somewhat lower than it, so that from a solid angle of about 30° in azimuth and 30° in elevation the radiation from the sea surface was replaced by that reflected from the radar dome. It can be shown that for isotropic radiation the fraction of the total flux intercepted by an obstruction is $(1 - \cos 2\delta)\phi / 4$, where δ is the elevation and ϕ the azimuthal angle subtended. For the angles subtended by the radar dome, this fraction amounts to about two per cent. This two per cent of the flux from the sea was replaced by the radiation reflected from the gray paint of the radar dome. The radiation incident on the radar dome in turn was that reflected by the sea surface, so that it is apparent that the flux replacing the two per cent obstructed was not much different from it. Thus the error introduced is probably considerably less than two per cent.

A second source of error arises from the deviations of the pyrheliometers from the horizontal. The pyrheliometers were mounted so that they would be horizontal in normal flight. Because of variations in temperature, wind, and pressure, the angle of the axis of the blimp varied from the normal position during the readings, and irregularities in vertical air velocities, and other factors, caused additional variations. In order to offset the accidental variations, each observation was made by averaging ten readings taken in a period of from one-half to two minutes. The systematic deviations from the horizontal could not be averaged out, however, but again here, because of the operation of the cosine law, the errors introduced are sufficiently small that they need not be considered. The following discussion will show this.

If I is the intensity of radiation coming from a solid angle dw and falling on a surface from a direction making an angle θ with its normal, the element of flux passing through that surface is given by

$$dF = I \cos\theta \, dw = I \cos\theta \sin\theta \, d\theta \, d\phi$$

$$= (I/2)d(\sin^2\theta)d\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where ϕ is the azimuthal angle.

Assume that the radiation in each direction is isotropic, and let I_+ be the intensity from any part of the cloud, and I_- that from any part of the sea. Then the flux of radiation passing downward through a horizontal unit area is

$$F_+ = \int_0^{2\pi} \int_0^{\pi/2} (I_+/2)d(\sin^2\theta)d\phi = \pi I_+$$

Similarly the upward flux is

$$F_- = \pi I_-$$

and the albedo of the sea is

$$a_S = F_-/F_+ = I_-/I_+ \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

When the blimp was tilted an angle γ, the flux reaching the upper pyrheliometer was reduced because a certain amount of radiation from above was replaced by radiation from below. This radiation was that coming through the lune of a unit sphere cut out by the intersection of the horizontal and the plane of the pyrheliometer surface. If the axis from which ϕ is measured is normal to the line of intersection, the integration of (1) must be taken from $-\pi/2$ to $\pi/2$ with respect to ϕ, and from a variable angle β to $\pi/2$ with respect to θ, where β is given by $\operatorname{cotan}\beta = \tan\gamma \cos\phi$. Thus the flux on the upper pyrheliometer is

$$F_{+0} = \pi I_+ - [(I_+ - I_-)/2] \int_{-\pi/2}^{\pi/2} \int_{\beta}^{\pi/2} d(\sin^2\theta)d\phi$$

$$= \pi I_+ - [(I_+ - I_-)/2]\pi(1 - \cos\gamma)$$

Similarly the flux on the lower pyrheliometer is

$$F_{-0} = \pi I_- + [(I_+ - I_-)/2]\pi(1 - \cos\gamma)$$

and the "observed albedo" is

$$a_{s0} = F_{-0}/F_{+0} = [2\pi I_- + (I_+ - I_-)\pi(1 - \cos\gamma)]/[2\pi I_+ - (I_+ - I_-)\ (1 - \cos\gamma)$$

$$= [2a_s + (1 - a_s)(1 - \cos\gamma)]/[2 - (1 - a_s)(1 - \cos\gamma)$$

Solving for the true albedo

$$a_s = [a_{s0}\ (1 + \cos\gamma) - (1 - \cos\gamma)]/[1 + \cos\gamma - a_{s0}\ (1 - \cos\gamma)]$$

$$= a_{s0} - [(1 - \cos\gamma)(1 - a_{s0}^2)]/[1 + \cos\gamma - a_{s0}\ (1 - \cos\gamma)]$$

Expanding $\cos\gamma$ in powers of γ, it is seen that the error is of the order of $\gamma^2/4$ for small angles. An error of 0.01 in the value of the albedo would correspond to a tilt of 12°. This large tilt occurred rarely if at all. The error due to tilt thus cannot change the albedo value by one per cent.

Another error which might enter is due to the fact that when the blimp was close to shore and sufficiently high some of the reflected light came from land rather than sea surfaces. The cosine law again indicates that this effect must be small, and a tabulation of the observed albedoes according to distance offshore showed no correlation.

A final source of error arises when the clouds are thin in spots or broken so that at times the Sun shines on the upper pyrheliometer, greatly increasing its reading. Because the Sun is not at the zenith, even at noon, the sea immediately below the blimp may be in shadow, and with the illuminated sea surface at some angle from the vertical, the cosine law results in a relatively smaller increase in the light reaching the lower pyrheliometer. In this case the observed albedo would be considerably too low. On the other hand, if the blimp is in shadow but the sea below is in sunshine, the recorded albedo will be somewhat higher than the true one.

Results of observations--A total of 117 determinations of the surface albedo (a_s) was made on 45 different days during the summer of 1945. The distribution of values obtained is shown in Figure 1.

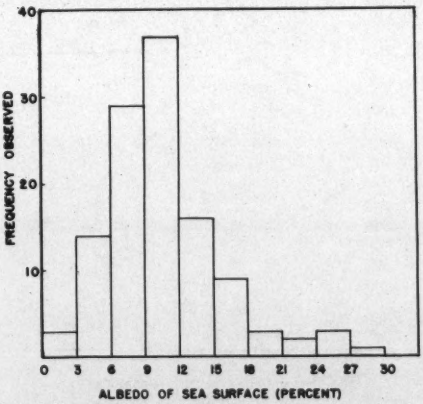

Fig. 1--Frequency of observed values of albedo of sea surface for diffuse radiation

The mean value of all observations is 10.5 per cent. The standard deviation is 5.0 per cent, and the standard deviation of the mean is thus 5.0/117 = 0.5 per cent. Thus if the measurements

are a normally distributed series of estimates of the same quantity, the probability is only five per cent that the actual mean deviates as much as one per cent from the mean of these observations. We may feel reasonably sure that the average value of a_s lies between 9.5 and 11.5 per cent.

Actually, the albedo might vary due to (1) the variation in character of the surface, and (2) the variation of the character of the incident light. Waves on the sea would increase the albedo over that for a smooth surface. If the clouds were so thin that the light were not truly diffuse, the albedo would be lower for the sun sufficiently high, and higher for low sun. Added to these real variations are the errors discussed earlier due to (3) scattering of light from particles in the air below the point of observation, (4) tilting of the blimp, and (5) irregularities in the cloud thickness.

As a measure of the character of the sea surface, the wind speed at the station nearest the point of observations was used. No correlation was found between this speed, which varied from calm to 30 mph, and the observed albedo.

The "degree of diffuseness" of the light, it seemed, would depend largely on the cloud thickness. Thus any variation due to this factor should be correlated with the cloud thickness. A slight correlation was found between the cloud thickness and sea surface albedo. When the light incident on the upper pyrheliometer was compared with the albedo a definite correlation was found. The variation of downward intensity below the cloud is due to (a) the variation of intensity on the top of the cloud, principally depending on the Sun's altitude, and (b) the optical thickness of the cloud, determined by geometrical thickness, water content, and drop size. Figure 2 shows the variation of albedo with Sun's altitude. If the light below the cloud were truly diffuse, the albedo would not depend on solar angle. Actually, the observed variation is greater than the theoretical variation for clear skies shown in the table. This indicates that the radiation passing through the cloud is not isotropic, but has definitely greater intensity in the direction of the Sun.

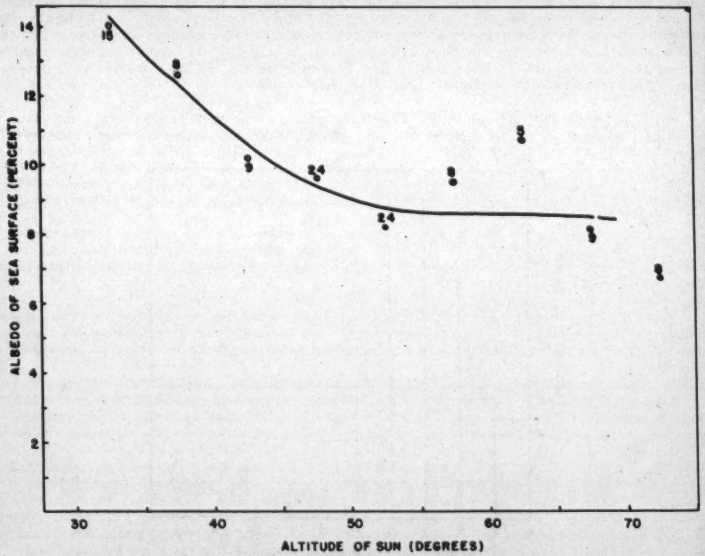

Fig. 2--Variation of sea surface albedo with solar altitude; numbers beside points give number of observations entering into average

Figure 3 shows that even for the same solar angle the albedo varies with intensity of downward radiation below the cloud. This variation may be due to either the variation of optical thickness

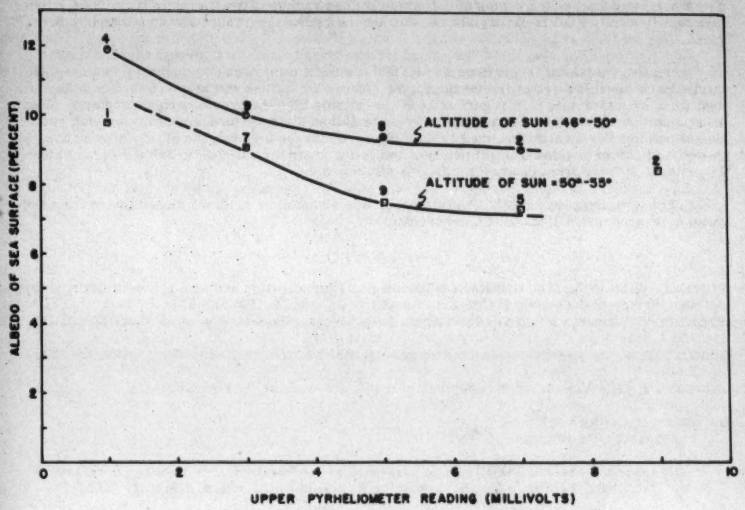

Fig. 3--Variation of albedo with intensity of downward diffuse radiation for constant solar altitude

of the cloud, or to errors produced by factor (5) above. Since there was found to be some correlation between albedo and geometrical cloud thickness, it seems safe to attribute at least some of the variation in albedo for constant solar angle to variation of degree of diffuseness. The fact that factor (5) would produce variations correlated in the same sense with the upper pyrheliometer reading makes it impossible to determine how much of the variation was due to such errors.

The albedo values were correlated with height of observation to see whether errors due to factor (3) were significant. The results were negative, indicating that this factor was of no consequence. The tilting of the blimp, factor (4), has already been shown from theoretical considerations, to be of little consequence.

The question of whether the several extremely large values are correct and due to particular conditions, or accidental erroneous measurements, was studied. No reason for doubting the measurements was found, nor was any physical reason why they should have been so large discovered.

Interpretation of observations--From the discussion of the observations it is seen that the radiation transmitted through stratus clouds is not diffuse. For high solar angles and optically thin clouds the radiation is least nearly diffuse, and the reflectivity of the sea surface for this radiation is as low as seven per cent. The variation with solar altitude is in the sense indicated by theory for clear skies, with high values for low Sun. This variation, however, is contributed to by the fact that for low Sun the radiation, following longer paths through the cloud, is more nearly diffuse than that for high Sun passing through the same cloud. In addition, the values for a constant solar angle show a steady increase with increasing optical thickness of the cloud. The data are not adequate to indicate whether the theoretical value of 17 per cent would be reached for extremely thick clouds. Nevertheless it seems fairly definite that the value for completely diffuse radiation is greater than 14 per cent and thus is not far from the theoretical value.

Thus for low Sun or thick cloud the probability is that Schmidt's value of 17 per cent should be applied, rather than Powell and Clarke's value of eight per cent in cloudy conditions. The latter figure should be used only for radiation from high Sun passing through relatively thin clouds.

Since the Schmidt figure for reflectivity of diffuse radiation is apparently correct, it follows that the albedo for a clear sky should be represented by line 2 of Table 1 rather than line 3.

Conclusions--The average albedo found for radiation transmitted through stratus cloud is 10.5 per cent, somewhat larger than Powell and Clarke's value, and considerably smaller than the value obtained theoretically by Schmidt for completely diffuse radiation. Based on a larger number of observations, it is regarded as more reliable than the previous measurements. The discrepancy from the theoretical value may be explained by the evidence showing that the radiation is not completely diffuse. Due to this it appears that for high Sun the albedo approaches Powell and Clarke's value of eight per cent, while for solar altitude 30° to 35° it has the value 14 per cent, not far from Schmidt's diffuse radiation value.

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MOVEMENT OF BEACH SANDS BY WATER WAVES

Hans Albert Einstein

Abstract--The basic similarity of the sand movement on a beach and in river flow is discussed and from this similarity an approach is indicated to the solution of the beach problem.

In studying nature we encounter many phenomena which obviously move or change their shapes continuously such as the clouds in the sky and the water in the streams. Others appear to be stationary and to undergo no changes whatsoever. We have learned and are still learning, however, that even the most stable of things like the rocks constituting the Earth's surface undergo changes. They may be slow, even so slow that they become imperceptible to our eyes, but they still exist. One of the major tasks of all natural science is the study of such changes.

The beaches which line a great part of our coast are constantly undergoing changes. Those who live near the coast will observe that the width of beaches increase and decrease with the seasons. They will notice also that a single storm may alter the appearance of a beach entirely and that it may take a considerable length of time until the beach has regained its normal appearance. Conditions become critical, however, when beaches begin to regress steadily and finally disappear. It is then that a search is made for the reason of these changes for which usually no satisfactory explanation can be found locally. They cannot be explained by especially severe storms or by any other obvious cause. Only when we begin to study the normal sand movements on a beach systematically do we begin to realize that the reasons for any such changes may be found at a distant part of the beach or even in a stream supplying sediment to the beach. An interruption of the sediment flow there may cause the beach to become denuded.

Systematic studies show that the sand moves slowly along a beach. This littoral drift often assumes proportions which suggest the possibility of describing the beach as a flowing river rather than as the shore of a stationary body of water. Upon closer observation we find more and more basic similarity between a beach and a flowing river: (a) In both instances a body of water is moving over a large deposit of loose sediment particles; and (b) in both cases we may observe that sediment particles are moved along with the water, sometimes at a large rate, sometimes at a small rate, sometimes only along the bottom, and sometimes suspended over the entire water depth. The motion of sediment, as caused by river flow, has been studied systematically by geologists and engineers for many years. The movement of sediment on a beach did not attract as much interest as the river problem until very recently. Thus, we are confronted with the problem of planning the basic lines of approach to be followed in studying the motion of beach particles.

As stated above, the motion of sand along a beach resembles in many respects the motion of sand in a river. This latter problem has been solved in large part, and it is reasonable to expect that a solution of the beach problem might be found by application of these same principles. The sediment motion in rivers was first described by means of more or less empirical expressions. It was realized that the rates at which sediment is moved depend both on the strength of the flow and on the characteristics of the sediment particles involved. It was found that the strength of the flow can be expressed by the "tractive force," which is another expression for the unit shear exerted on the bed by the flow. The sediment of the bed may be described by a representative grain diameter and by its specific gravity. Flume experiments were used to determine the relationship between these variables. A great number of empirical formulas were proposed by different investigators. Each formula is applicable only under conditions similar to those for which the specific formula was derived. None can claim general applicability. There is very little hope that any one of these formulas may be applied to the beach problem. The greatest obstacle besides their small range of applicability is the fact that there is no continuous flow at the beach which would permit the determination of a representative shearing stress. Instead, the motion of the particles is generated by the oscillatory water movement due to wave action. The major part of this motion has its direction at right angles to the beach line. Correspondingly, the major part of the sediment motion is oscillatory and directed at right angles to the beach.

This much one can very easily observe on every beach. If the waves which create the surf approach with long crests parallel to the beach, the resulting water velocities are all directed at right angles to the beach and no long-shore movement of sediment can result. If the waves approach the beach at an angle and if the resulting oscillatory motions are symmetrical like the ocean waves in deep water, we should expect that the long shore-components of the velocities also are symmetrical. This means that we could not expect to find a resultant littoral drift to occur. In reality, however, all waves become asymmetric in the shallow water of the beach and finally break. Then velocities of the water particles must be described as an oscillation superimposed over a current at any point of the flow. If these current velocities are integrated over a beach cross section, it is found that the average current in a direction perpendicular to the beach becomes zero; while the components parallel to the shoreline give a resultant flow which is largely concentrated in the region between the breaker point and the shore. Must this current be introduced as a driving force into the bed-load equation or must it be combined with the oscillatory flow in order to predict the littoral sand movement? The existing empirical approach to the sediment transportation problem unfortunately cannot answer this question.

From this short analysis it becomes apparent that the beach problem is more complicated than the corresponding river problem. The littoral current which causes the littoral sand movement is a small secondary part of the flow while, in the river, sand motion is caused by the main flow itself. The pattern of the two motions is, therefore, different and we cannot expect them to be described by the same equations.

This seems to contradict our first statement that the two types of movement are basically similar, but it does not. Basic similarity between two physical phenomena does not necessarily imply that they are described by identical equations. It only means that the fundamental concepts which are used in the derivation of the equations are the same. For instance, it may mean that both occurrences follow the same basic differential equation which must be solved individually for each case. If we want to learn anything from the river problem that might be applicable to the beach problem, we must look for basic facts rather than final results. It is difficult if not impossible to define with a sentence what a "basic fact" is; however, an attempt will be made to enumerate some observations which have been made in the river problem and which may apply in the beach problem.

(1) It has been found that sediment particles can be suspended indefinitely in a turbulent flow. The vertical velocity components in the turbulent flow move sediment particles from lower layers with higher concentrations to higher layers with lower concentrations at a larger rate than in the opposite direction. An equilibrium condition is reached when the resulting upward movement of particles due to turbulence is just sufficient to counteract the normal settling of the sediment particles in water. This same description probably is applicable to the beach problem, but the application of the theory to practical beach problems is considerably more complicated than to stream problems unless the periodic changes of turbulence can be neglected.

(2) In the calculation of suspended load distributions it is possible to make a number of simplifying assumptions in the case of rivers. For instance, can the settling velocity of a particle, as determined in still water, be applied in turbulent flow? Furthermore, the turbulence in a river which embraces a very complicated pattern of constantly changing flow velocities in all directions can be sufficiently described for this problem by only an average value of the vertical velocity component. There is no reason why these shortcuts should not be equally valid for the beach problem.

(3) In a thin layer near the sediment bed the theory of suspension breaks down, and the particles there are not vertically supported by the flow turbulence in the case of the river flow, because at this point the scale of the turbulence becomes very small. The particles roll on the solid bed, instead. This zone has been called the "bed layer" and is about two grain diameters thick. The sediment which moves in this layer is usually called bed load. This same phenomenon may be expected to occur in the beach problem.

(4) In a river it has been found that a constant exchange of sediment occurs between the bed and the bed layer. The number of particles which are deposited every second in the bed depends on the rate of bed-load movement. The number of particles which are removed from the bed every second depends mainly on the flow pattern. The equation which expresses equality of the two rates is the bed-load equation for a stable bed. A similar equation also must exist for the beach problem. It is not clear, however, how the periodicity of the flow must be introduced into this equation, when the flow pattern is described.

(5) In deriving the bed-load equation for river flow it is sufficient to introduce the flow conditions in the immediate vicinity of the bed. This fact is probably correct also for the beach problem.

(6) The rate at which bed load is being deposited in the bed has been found to be proportional to the rate of bed-load movement and inversely proportional to the distance traveled by the bed-load particles between periods of deposition. This fact was observed for river flow and probably holds also for the beach problem.

(7) If the sediment bed of a river consists of various grain sizes, each grain size moves as if the entire bed consisted only of particles of this type. This basic independence with which the different fractions of a mixture move also can be used, with all probability, to describe the sediment movement on beaches.

Still more "basic facts" of this type probably could be enumerated. Together, they mark a definite line of attack which was successful in describing the river problem. The great difficulty in the case of the beach problem is our complete lack of knowledge concerning the flow details, especially the turbulence distribution. It seems that much basic hydraulic research is necessary for the beach problem before the sediment problem can be fully understood. Unfortunately, the turbulence studies conducted in wind tunnels which gave practically all the required information for the river problem are not directly applicable to the periodic flow on the beach.

Besides these basic studies, where the aim is to derive sediment transportation laws through analogy with the corresponding river problem, it will be necessary to make sediment measurements on natural and model beaches to check and support any such theoretical approach.

The stability of beaches is closely connected with the construction and maintenance of harbor installations. For this reason several public agencies have recently shown considerable interest in this problem. Geologists and oceanographers on the other hand have a large scientific interest in the solution of the sediment problem on beaches. It would be very desirable if these different efforts could be coordinated under a common program of systematic research.

Acknowledgment--This paper is an excerpt of the basic ideas given in a report entitled "Some thoughs on the organization of research on the movement of beach sands by water waves" for the Navy Wave Project at the University of California.

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METAMORPHIC AND VOLCANIC ROCKS FROM THE D'ENTRECASTEAUX ISLANDS

G. Baker and A. Coulson

Abstract--Acid and basic regional metamorphic rocks are described from Goodenough and Fergusson Islands. Quaternary volcanism has broken through the metamorphic complex to form a basaltic lava cone at Olava-ai in northern Goodenough Island, and basaltic lava flows on the eastern side of the island. Northeast of Fergusson Island, the islands of the Amphlett Group are exclusively andesitic.

Introduction--The metamorphic and volcanic rocks described herein were collected by A. Coulson during the War from the northern part of Goodenough Island, from Debe in the northwest of Fergusson Island, and from Urasi Island in the Amphlett Group. Several of the smaller islands in the Amphlett Group were also visited, and found to be built up of volcanic rocks similar to those obtained from Urasi Island. These islands are all members of the larger island arc constituting the D'Entrecasteaux Islands (see Fig. 1), situated 30 to 40 mi northeast of the southeastern tip of New Guinea, and 200 mi south of New Britain. Little is known of the regional geology and the principal purpose of this report is to make a small contribution to the petrology of the region.

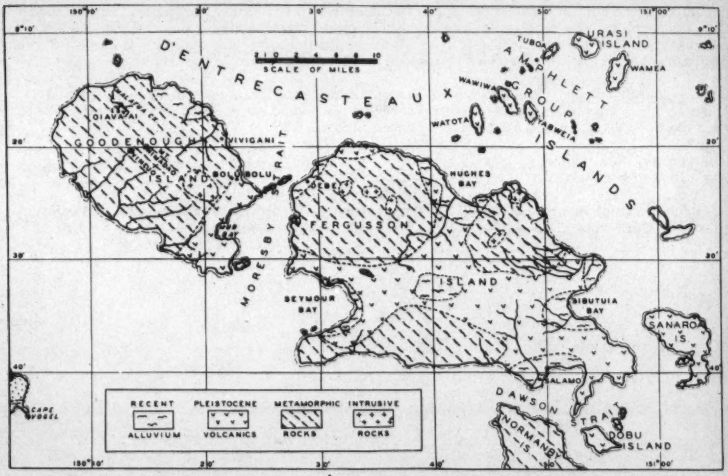

Fig. 1--General geological map of the D'Entrecasteaux Islands based on Australian Army map of Fergusson Island, first edition, 1942, on STANLEY'S [1919] geological map of Fergusson (Moratau) Island, and on the geological map of Papua by GIBB MAITLAND, CARNE, STANLEY, and WADE [1914].

The cores of the larger islands, such as Goodenough, Fergusson, and Normanby Islands, are composed of regional metamorphic rocks and some associated intrusive igneous rocks which, on Fergusson Island, are referred to by STANLEY [1920] as doleritic and gabbroid dykes, plutonic apophyses of more acid composition, and granite masses. The islands are apparently the higher remnants of a drowned section of the New Guinea cordillera. The larger islands are partly covered by later volcanic rocks classified as of Pleistocene age on the Geological Sketch Map of

Eastern New Guinea (prepared by the Directorate of Research, L. H. Q., Melbourne, December, 1944, from information supplied by J. N. Montgomery, N. Osborne, and M. F. Glaessner). Alluvium and hillwash deposits cover the slopes of the larger members in this island arc.

The Amphlett Group of islands is made up of volcanic rocks (see Fig. 1). They have been built up from the sea floor to 230 ft in Wawiwa Island, to 417 ft in Tuboa Island, to 602 ft in Watota Island, to 1420 ft in Urasi Island, to 1500 ft in Wamea Island, and to 1921 ft in Yabweia Island. A few small coral islands also occur, while coral reefs have been developed offshore from some of the larger islands.

The metamorphic complex--The age of the metamorphic complex is at present unknown; in the area under consideration, it would seem to be pre-late Cenozoic. It is surmised to be at least pre-Mesozoic in the New Guinea area generally, although STANLEY [1920] referred to the schistose series as Huronian and pre-Algonkian.

The trend of the banding in the metamorphic rocks, is generally northeast-southwest in cliff exposures at the northern end of Goodenough Island and at the northern end of Fergusson Island. No other structural data are available to add to the little already known for this area.

Fig. 2--Geological map of the Oiava-ai district, northern Goodenough Island, based on Australian Army map 2064, Goodenough Island, 1:1 inch series, 1943

The metamorphic rock types are varied. In the northern part of Goodenough Island, in the Oiava-ai region (see Fig. 2), are hornblende-biotite schist, granite gneiss, muscovite gneiss, biotite gneiss, hornblende-biotite-diopside gneiss, garnetiferous-hornblende gneiss, biotite amphibolite and epidote amphibolite. These rocks were obtained during a traverse which included the native villages of Mwananoia, Laukolateia, Kakaweadiaeia, Matala, Ahameia, Wataluma No. 2, Budula, shown in Figure 2, and on to Vivigani (see Fig. 1) on the northeast coast. (The author advises that the discrepancies in latitude and longitude, revealed by comparison of Figures 1 and 2, were caused by the different base maps used.) The same rock types constitute the high ranges to the south of these localities; the ranges rise to an average height of 7000 ft, with Vineuo rising to 8350 ft, Oiautukekea (one mile east of Vineuo) to 8000 ft, Mt. Nimadao to 7750 ft, and Oiamadawa-a (two miles northeast of Mt. Nimadao) to 7090 ft.

In the vicinity of Bolu Bolu (see Fig. 1) on the eastern side of Goodenough Island, are hornblende-epidote schist, biotite gneiss, garnetiferous-muscovite gneiss, zoisite amphibolite and epidote-albite amphibolite. These rocks were taken from a terrace deposit about 100 yards from the beach near Bolu Bolu. They must have come from hills underlain by metamorphic rocks west of Bolu Bolu because they were deposited by a stream draining these hills. The rock types mentioned here are, in general, similar to those collected in situ from the northern portion of Goodenough Island.

The more common metamorphic rock types on Goodenough Island are the lighter colored gneisses such as granite gneiss and muscovite gneiss. The biotite gneiss and other dark-colored metamorphic rocks of greater specific gravity are rather uncommon. Micaceous quartz schists dipping south-southwest at 30° - 40°, and garnetiferous hornblende schists, have been recorded by GIBB MAITLAND [1892] at the southwest end of Normanby Island.

Hornblende-epidote-zoisite schist occurs in the Debe district (see Fig. 1) on Fergusson Island; the rock was obtained from Debe plantation, where metamorphic inliers occur in a narrow bench of coral limestone raised some ten to 15 ft above sea level.

Mineralogy of the metamorphic types--Among the metamorphic rock types from the northern part of Goodenough Island, the hornblende-biotite schists contain small grains of sphene surrounding clots of titaniferous iron oxides, rutile and apatite and small amounts of orthoclase and albite. The hornblende is typically the bluish-green to greenish-yellow-brown variety, probably containing small amounts of the soda molecule. The biotite amphibolite, although relatively fine-grained, is nevertheless somewhat coarser than the hornblende-biotite schist, and does not show such marked foliation. The feldspar in it is principally albite; apatite crystals are common; quartz and calcite occur occasionally.

The granite gneiss is white, and is probably an ortho-gneiss. It is fine to medium-grained. The main constituents are quartz and feldspar with orthoclase dominant over oligoclase. There are a few small flakes of brown biotite and muscovite and some myrmekitic intergrowths. Hornblende is rare. Accessory minerals are apatite, euhedral zircon including a rare, pale pink variety, sphene and magnetite. The texture and the mineral assemblage suggest a granulated and partially recrystallised granitic type, with cataclastic textures pronounced in parts. Other light-colored gneisses, such as the muscovite gneiss, are generally similar to the granite gneiss mineralogically and texturally, but some examples are garnetiferous. The garnet is almandite and occurs as relatively clear, brownish-red crystals.

In the biotite gneiss, cyanite occurs armored with biotite and is also associated with muscovite. The hornblende-biotite-diopside gneiss, a medium to coarse-grained rock, contains a pale greenish variety of diopside, and also carries a small amount of introduced calcite and pyrite. Some of the hornblende gneisses are also garnetiferous, but in them, the common variety is pyrope. The garnet characteristically possesses numerous, minute, colorless inclusions arranged in a haphazard manner. These rocks are fine-grained and occasionally traversed by quartz veins; they also contain sphene and yellow rutile, which, with iron ores, are often included in the bluish-green hornblende. Zoisite and some ferriferous epidote have been developed as well.

Epidote amphibolite, which is composed largely of blue-green to yellow-green masses of large and small hornblende crystals, some acicular, contains a variety of epidote which does not have the typical pistachio-yellow color of ordinary epidote. It is probably only slightly ferriferous. Small quantities of orthoclase and poikiloblastic albite are interstitial; the albite carries yellow, euhedral rutile crystals, and numerous apatite needles.

In the hills west of Bolu Bolu, eastern Goodenough Island, the mineralogy of the metamorphic rock types is comparable with that of the rocks in the northern part of the Island. The lighter-colored rock types are again predominant, although biotite gneiss is well represented. The biotite gneiss from the Bolu Bolu region contains myrmekitic intergrowths, strained quartz crystals, oligoclase dominant over orthoclase, greenish-brown biotite, occasional chlorite and apatite. The considerable range in grain sizes is probably due to cataclasis; the rock apparently is a crushed and partially recrystallised granodiorite.

The zoisite amphibolite is coarse-grained. The zoisite is well developed and is associated with actinolite, tremolite, some diopside and serpentinous decomposition products, minor quartz, and blue-green hornblende. The hornblende in places occurs as radial aggregates. Other zoisite amphibolites from the Bolu Bolu district are particularly rich in zoisite. Abundant sagenitic networks, clots, and granules of iron ore minerals commonly occur along the cleavage directions in the blue-green and partly actinolitic hornblende. In such rocks, albite is rare and associated in one instance, with even rarer quartz to form an "augen structure" in the actinolite. Veins of quartz, sometimes with associated calcite, traverse parts of the epidote-zoisite amphibolite.

In the hornblende-epidote-zoisite schist from Debe Plantation in the northwestern portion of Fergusson Island, the amphibole is blue-green and is accompanied by some sphene and quartz.

Nature of the metamorphic changes--Whereas the granite gneiss from northern Goodenough Island and the biotite gneiss from the hills west of Bolu Bolu represent regionally altered granite and granodiorite respectively, the denser and darker-colored metamorphic rocks from Goodenough and Fergusson Islands probably represent the regionally altered products of original basic igneous types of the gabbro-dolerite group.

In the more basic derivatives, the original augite has gone to secondary hornblende, while the diopside in most instances altered to tremolite with epidote, zoisite, and quartz as by-products. All of the original textures of the parent rock types have been lost during the mineral transformations, but where diopside occurs in some of the metamorphic rocks, it may represent a relict mineral. The garnet in the hornblende gneisses of the D'Entrecasteaux metamorphic complex was identified by refractive indices, as pyrope. The pyrope is thought to have developed from reaction between the anorthite molecule in the original feldspars and olivine or some basic, ferromagnesian constituent in the parent rock type. This reaction also produced small amounts of albite-oligoclase feldspar as a by-product. The garnet in the muscovite gneisses appears to be almandite and to have developed from a reaction involving the release of iron from the biotite molecule during the formation of white mica, and alumina from the feldspars during partial recrystallization.

Throughout the different metamorphic grades of regionally altered rocks in the D'Entrecasteaux Islands, there is a characteristic loss of iron and birefringence evident among the epidote group of minerals. As the grade of metamorphism increases, zoistite becomes increasingly important as an idioblastic constituent culminating in the highest grades as the principal representative of the epidote group in some of the amphibolites.

Many of the original rock types evidently contained considerable lime which entered into the composition of such minerals as epidote, zoisite, and hornblende, minerals that are so preponderant among the more basic metamorphic derivatives of the D'Entrecasteaux Islands. Excesses of titania over and above that needed for titaniferous iron ores, recrystallised to form granular aggregates of sphene and euhedral crystals of rutile. P_2O_5 formed numerous needles and occasional stouter prisms of apatite. Soda went into albite, although some undoubtedly entered the hornblende molecule, especially the characteristic blue-green variety. Apparently there was only a slight amount of potash available during the metamorphic changes of these more basic rocks after the formation of biotite. Orthoclase is present in very small amounts.

The regional metamorphic rock types of the D'Entrecasteaux Islands are such as to indicate an original complex of acidic and basic rocks, principally igneous, with the acid group preponderant. Probably some greywackes or argillaceous sediments also were represented among the parent rocks. Changes in mineral composition, textures, and structures were due mainly to recrystallization accompanied by slight cataclasis as a consequence of dynamo-metamorphism during the orogenesis that had long preceded the initiation of the Upper Tertiary-Recent Vogel Geosyncline [CAREY, 1938].

The foliated types point to the existence of unequally distributed stresses during the orogenesis that resulted in the formation of the D'Entrecasteaux metamorphic complex. This complex is also known to occur along the core of the island of New Guinea. The foliated basic metamorphic

derivatives with some quartz, comprise the hornblende gneisses. Some types were less basic, and thus, contain biotite as an additional ferromagnesian constituent in the hornblende-biotite gneisses. The biotite gneisses are more acid and are related to the hornblende gneisses. The hornblende-biotite gneiss is a transitional phase between the two.

The regionally altered rock types of this area indicate intermediate zone conditions (Mesozone) of metamorphism with considerable temperature, uniform pressure, and some strong directed pressure. Stress minerals like muscovite, albite, the epidote-zoisite group, amphiboles, and a little cyanite were typically formed.

The volcanic rocks--The volcanic phase is late in the geological history of the D'Entrecasteaux Islands. It is represented by the development of basalt on Goodenough and Dobu Islands (and probably on Fergusson Island), and by the formation of andesitic volcanic islands in the Amphlett Group. The basalt and andesite are probably Quaternary and not greatly separated in time. Prior to the development of volcanism in this area, the metamorphosed rocks of the region had been subjected first to prolonged erosion, then to downward crustal movements. These movements resulted in the drowning of the more prominent valleys, now represented by Moresby Strait, separating Goodenough and Fergusson Islands, and by Dawson Strait, separating Fergusson and Normanby Islands (see Fig. 1). It was upon the higher remnants of this partially drowned region that the basaltic lavas were poured out. In the northern part of Goodenough Island, Oiava-ai is a basaltic volcano that has broken through the core of crystalline metamorphic rocks which here form the northern flanks of the main metamorphic range of the island (see Fig. 3). It has been built up on these flanks within the area of the 400-ft contour for at least 1000 ft. Its summit is 1400 ft above sea level. Small flows occurred to the north along Malafua Creek, but otherwise the basalt did not extend very far laterally in this district. This fact suggests a greater viscosity than is usual for basaltic lava. As a consequence, the basalt lava, already in an advanced stage of crystallization, as evidenced by its well-developed porphyritic character, piled up to a thickness of at least 1000 ft, while only spreading laterally a maximum of some 5600 ft.

Basalts--The volcanic cone of Oiava-ai is composed principally of porphyritic basalt with a dense groundmass. A band of vesicular basalt, up to five ft thick with numerous small gas cavities, occurs at about 500 ft altitude and provides the only example of distension of the basalt lava by the escape of mineralizers. Above and beneath this band, the lava is characteristically a dense, dark blue-green, porphyritic basalt with phenocrysts of olivine. It generally appears fresh and rings like phonolite when struck with a hammer. Some of the more fissile portions of the flow below the 500-ft level split readily into large flags.

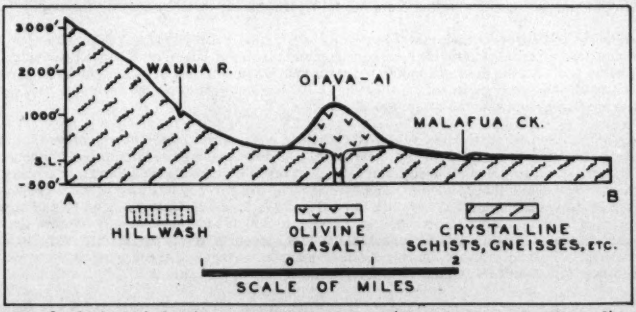

Fig. 3--Geological sketch section through Oiava-ai (along the line A-B of Figure 2), showing the relationship of the Quaternary volcanic rocks to the metamorphic complex

Thin sections of the basalt from Malafua Creek, on the western side of Oiava-ai, reveal that the olivine phenocrysts are unaltered and that phenocrysts of pale green augite and labradorite are also present. These are set in a dense, dark gray, microcrystalline to hyaline groundmass containing small laths of andesine-labradorite showing partial fluidal alignment. The dark gray color is caused by finely disseminated iron ore minerals, which, in the more weathered vesicular basalt, have been altered throughout to limonite. Here and there, in parts of the flows, narrow

rims of iddingsite have been formed around the olivine phenocrysts, as well as along cracks in this mineral. Iddingsite also occurs in occasional isolated patches in the groundmass. The iddingsite in the Oiava-ai basalt is a deuteric mineral resulting from the oxidizing reaction of volatiles in the lava on olivine during the final stages of cooling rather than a weathering product, as shown by EDWARDS [1938] for some of the Victorian basaltic rock. This is borne out by the extreme freshness of the flows containing iddingsite.

The iddingsite, characteristically a brittle mineral, shows neither fragmentation nor distortion in olivine basalt from Malafua Creek, suggesting that the basalt lava had ceased to flow before the development of iddingsite [ROSS and SHANNON, 1925; and EDWARDS, 1938]. Furthermore, it is a mineral of late development in this basalt, because it is not rimmed by olivine and augite as described by EDWARDS [1938] in some Victorian iddingsitised basalts where iddingsite formed before complete crystallization of olivine and augite and was surrounded by them. Embayment of some of the olivine phenocrysts by groundmass constituents in the Oiava-ai basalts indicates that the olivine had become somewhat out of equilibrium with the system and was partially resorbed. The embayment occurred before the formation of the iddingsite as evidenced by iddingsite rims following the outlines of the embayed portions of the olivine.

In some of the flows from Oiava-ai, phenocrysts of both olivine and labradorite are more equally developed and abundant than in others. In them, the groundmass is holocrystalline, and is composed of labradorite laths, augite grains, and needles and granules of iron ore minerals. Such portions obviously cooled more slowly, so that most of the labradorite phenocrysts have narrow, clear rims around a zone filled with earlier crystallization products. The inner cores are quite clear, and the structure thus indicates that clarification of the growing labradorite phenocrysts had not been completed before final consolidation. Such representatives of the Oiava-ai flows are best distinguished from the olivine basalt and iddingsitised olivine basalt as olivine-labradorite basalts.

Parts of the groundmass of the normal olivine basalt are distinctly tachylitic in character, and such types are thus inclined to be vitrophyric.

In the vesicular basalt from Oiava-ai, the fluidal alignment of small, lath-like crystals, is more pronounced. The crystals are set in a brown to colorless glassy base. The brown color is a stain resulting from secondary iron hydroxides or weathering. One portion of the vesicular flow from Malafua Creek contained a xenocryst of quartz with a small amount of attached albite. The xenocryst was obviously picked up by the lava as it broke through the crystalline complex of gneisses. The more highly weathered parts of the vesicular basalt show the olivine altering along cracks to serpentinous products. The augite is fresh, but the labradorite laths have altered to an indefinite, isotropic material. Vesicular basalt also occurs on Dobu Island.

At Bolu Bolu, 15 mi southeast of Oiava-ai, on the eastern side of Goodenough Island, the lavas are mineralogically and texturally comparable with those from the Oiava-ai-Malafua Creek district. Porphyritic basalts are more extensively developed and contain comparable quantities of iddingsite in the olivine phenocrysts. The basalts were no doubt derived from the same magma chamber that gave rise to the Oiava-ai lavas. They seem to be more spread out laterally, or else there were more centers of eruption.

Andesites--The lavas of Urasi Island (see Fig. 1) and the nearby islands in the Amphlett Group are typically hornblende andesites with some hypersthene. They frequently show marked color banding due to the alternation of leached zones with zones in which the dissolved materials mainly iron hydroxides, were deposited. The leaching is the result of weathering.

The andesites contain reddish-brown to yellow hornblende phenocrysts with strongly developed reaction rims which are now chiefly broad bands of hematite and limonite. Many augite crystals have reaction rims of hornblende. Some of the andesine phenocrysts are well-zoned and occasionally corroded. Hypersthene is rare. The groundmass is microcrystalline to hyaline.

On the islands of Watota, Yabweia, Wamea, Tuboa and Wawiwa (see Fig. 1), volcanic rock types similar to those on Urasi Island, show like volcanic structures. The islands consist of steep volcanic peaks rising out of the South Pacific Ocean with large and impressive columns of lava forming steep cliffs. The lava columns are only roughly outlined and not as well jointed as in organ-pipe structures.

Nature of the volcanism--Andesitic types, some with a little hypersthene, are well represented among the lavas of the D'Entrecasteaux Islands. This is in accordance with the fact that the

volcanic eruptions girdling the Pacific Ocean are mainly andesitic and are also hypersthene-bearing. In the southeastern New Guinea region, the andesitic lavas of the Amphlett Group of islands are to be associated with a magma reservoir that is still supplying andesitic volcanic material. This is evidenced by the recently erupted Goropu volcano in the Collingwood Bay region of southeastern Papua [BAKER, 1946], about 120 mi to the west of the Amphlett Group. The volcanoes of the Amphlett Group, however, represent a considerably earlier stage of the andesitic phase of eruption, since the bulk of the volcanic material from them consists of lava flows, and therefore the eruptive stage is the principal one. In the Goropu Mountains, on the other hand, the dying phases of eruption are evident in the basence of lava flows (as far as is known at present), and in the fact that the volcanism is confined to the explosive type with associated gaseous and sulphurous emanations.

GIBB MAITLAND [1892] referred to the prevalence of andesitic lavas on the southwest coast of Fergusson Island. He described some of the volcanic cones there as consisting of stratified volcanic ashes, some breached by andesitic lava flows. The only activity evident at the time of Gibb Maitland's visit in 1891 was the emanation of steam and gas with the deposition of native sulphur. Similar conditions were noted on Dobu Island.

It is thus apparent that the development of andesitic lava and ash volcanoes has been relatively widespread in the D'Entrecasteaux Islands. The volcanism was not entirely restricted to the formation of andesitic types, however, as there are basaltic lavas south and southwest of Bolu Bolu and at Oiava-ai on Goodenough Island (see Fig. 1). Moreover, CLARKE [1892] described rhyolite-obsidian from Fergusson Island, as well as vesicular basalt from Goodenough Island. STANLEY [1919], shows late Tertiary to Recent volcanic rocks on Fergusson Island, Dobu Island and Sanaroa Island, with geysers, fumaroles, and hot springs, on the southwest and southeast peninsulas of Fergusson Island. The petrographic types are varied; namely, pumice, obsidian, rhyolites, andesites, volcanic sediments, and others. STANLEY [1920] considered that the volcanic disturbances in the D'Entrecasteaux Islands were most severe during late Tertiary subsidence, and followed emergence that began in early Tertiary times. Judging from their extreme freshness, the basaltic types of lava examined from the D'Entrecasteaux Islands were apparently poured out in geologically Recent times.

There is also some evidence pointing to the existence of yet another type of lava not referred to by earlier workers in this region. Among the rocks collected from near Bolu Bolu on the eastern side of Goodenough Island, is a rare type, best classified on thin section evidence, as dacite. It is pinkish and contains embayed and rounded quartz phenocrysts, some zoned oligoclase, occasional orthoclase, and green to pale yellowish-green biotite set in a crypotocrystalline to microcrystalline groundmass of quartz and feldspar with some apatite. The rock has been so altered that it is probably an older flow than the basalts and andesites of the D'Entrecasteaux Islands. The biotite is occasionally sheared, with limonite occurring along the shear lines. Quartz veins cut through the fine-grained groundmass, along the cleavages of feldspar phenocrysts, around biotite plates and through quartz phenocrysts.

The considerable variety of volcanic rocks represented in the D'Entrecasteaux Islands, ranging from basic to acid types, indicates that there must have been considerable differentiation of the basaltic magma in these parts of the volcanic girdle fringing the Pacific Ocean. The acidic types were apparently poured out first and the basaltic lavas were extruded late, or at least considerably later than the main outpourings of andesitic types.

Recent deposits--The larger islands of the D'Entrecasteaux Group, particularly Goodenough Island, have strikingly bold topographical outlines for their size. Goodenough Island is only 23 mi long and 15 mi wide, but rises steeply to 8350 ft near the center of the island. The north-flowing streams, such as the Wauna River (see Fig. 2) therefore have a high gradient, falling about 7000 ft in seven mi on the average; in the higher reaches of the stream courses, however, the fall is 6500 ft in four mi (that is, 1 in 3). The result of such steep gradients has been the spreading of considerable amounts of hillwash over the lower flanks of the main range in the north, from the 400 ft contour line down to sea level. Stream gradients in the north are only one in 7.5. The streams must, therefore, be vigorous and erosion of the metamorphic complex is considerable. The outwash material is composed of coarse gravels derived from the metamorphic rocks, with occasional large boulders. The Wauna River is most active in the transport of the disintegration products of tropical weathering of the metamorphic rocks, and its course is much braided northwest of Oiava-ai. After heavy torrential rains, it links up with Malafua Creek.

Coral islands and coral reefs are frequent features of the D'Entrecasteaux Group. The small islands between Goodenough and Fergusson Islands, situated east of Bolu Bolu, form a group of

low coral islands up to only ten ft above sea level. Associated coral reefs probably represent drowned coral islands. All of the islands of the D'Entrecasteaux Group possess numerous fringing coral reefs, and these are especially marked off the north coast of Goodenough Island, and off the southwest coast of Fergusson Island.

Raised coral limestone is evident at the northeast end of Goodenough Island, and at Hughes Bay, Seymour Bay, Sibutuia (Hygeia) Bay, and around Salamo on Fergusson Island. Salamo itself is situated on coral rock about 15 ft above sea level, with mangrove swamps along the shores. There are thermal springs about two mi inland. Debe, on the northwest side of Fergusson Island, is also situated on coral limestone some 15 ft above sea level. Such regions are associated with superficial material, represented on Figure 1 as alluvium.

Conclusions--The investigations covered by this article, show that the basement rock of the D'Entrecasteaux Islands consists of a metamorphic complex, composed principally of acidic regional metamorphic rocks, with some associated basic types. Additional metamorphic rocks, not recorded herein, are indicated as occurring in Fergusson Island on the geological map of Fergusson (Moratau) by STANLEY [1919]. These additional types are quartzites and marble. It is therefore evident that the pre-metamorphic terrane contained not only predominantly acid igneous parent rocks with some basic types and occasional argillaceous sediments or greywackes, but also sandstones and limestones. After orogenesis and regional metamorphism of these rocks, thermo-metamorphic provinces were developed around the limited intrusions of plutonic rocks, marked as granites and pegmatites on Stanley's map. Portions of the regional metamorphic complex have therefore been altered a second time with the introduction of veins of quartz and epidote [STANLEY, 1920, p. 20]. The plutonic intrusions and the thermo-metamorphic provinces, represented as small scattered outcrops on Fergusson Island, have been exposed only after prolonged erosion.

Volcanism, at a much later geological period, was apparently associated with sinking of the area and the development of geosynclinal conditions; namely, the formation of the Vogel Geosyncline which still persists today. The end stages of volcanism are evidenced in this area today by the occurrence of the hot springs, fumaroles, and geysers referred to by GIBB MAITLAND [1892] and by STANLEY [1920] in various parts of the southeast and southwest portions of Fergusson Island and the nearby smaller islands, such as Dobu and Sanaroa Islands.

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SIZE OF RAINDROPS AND THEIR STRIKING FORCE AT THE SOIL SURFACE IN A RED PINE PLANTATION

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Abstract--It is usually assumed that a forest canopy breaks the force with which rainfall strikes the soil, thus protecting it from erosion. To show that this is frequently untrue and that the protective value of the forest to the soil must, therefore, be due to lesser vegetation or to the layers of unincorporated organic material lying on the soil surface is the purpose of this paper.

Measurements were made of raindrop size beneath a red pine canopy and in an adjacent open field near New Haven, Connecticut during several storms in 1946 and 1947. By reference to published tables of velocities of falling water drops, the kinetic energy at the soil surface of the rain under the pine canopy and in an open field was determined. It was found that at rates of precipitation less than two inches per hour the kinetic energy of rainfall beneath the red pine canopy exceeded that of rainfall in the open.

Introduction--Although the protective value of forest litter has been appreciated for many years both as a result of conditions in such European forests as the one described by GLEISSNER [1914] where continual removal of the litter resulted in erosion as serious as on unforested, bare soil and also through experiments such as those of LOWDERMILK [1931] who found up to 6000 times as much material eroded from soils burned bare as from soils covered by a litter layer, the protective value of the living forest cover has, on the other hand, usually been assumed and rarely tested conclusively.

Forest growth may either increase or decrease the quantity of precipitation reaching the forest soil and it may also change the nature of the precipitation (1) by breaking raindrops into drops of smaller size; (2) by combining raindrops into larger units; (3) by reducing the velocity with which the precipitation strikes the soil; (4) by increasing the length of time during which the precipitation falls; or (5) by conducting a part of the precipitation to the ground along branches and stems. Any of these changes could obviously affect the rate of runoff and the amount of soil erosion.

Although under special climatic conditions, atmospheric condensation on tree canopies may increase the amount of precipitation in a forest, in the vast majority of cases the effect of living canopies is to decrease the amount of rainfall reaching the forest floor as is shown by numerous comparative measurements that have been made between rainfall under tree canopies and in nearby open areas. Because of the number of factors involved, these interception measurements have varied over a considerable range. The fact remains, however, as noted by ZON [1927] that although a rather large proportion of precipitation will remain in the tree crowns when rains are neither heavy nor of long duration, the ground under forest, no matter whether the latter is deciduous or coniferous, will receive as much or nearly as much water as bare ground when precipitation is in the form of heavy or prolonged rains, the form that causes the greatest erosional damage.

Perhaps more important than quantitative changes are the qualitative effects of forest growth on precipitation, that is, changes in drop size and in the force with which precipitation strikes the mineral soil surface. This statement seems to be borne out by the work of BORST and WOODBURN [1942] who compared the soil losses resulting from the application of artificial rainfall to a bare soil, to a soil covered by a mulch and to a soil having a mulch supported an inch above its surface, and concluded that the elimination of raindrop impact with its destructive effect on the surface soil rather than the reduction of overland flow velocity appeared to be the major contribution of the mulch in reducing soil loss.

Likewise the findings of LAWS [1940] that erosional losses measured in terms of the concentration of soil in the runoff water increased by as much as 1200 per cent as drop sizes were increased and that the rate of infiltration, after three-quarters of an hour of rainfall, decreased with an increase in kinetic energy of the drops falling per unit area, place the stress on qualitative aspects of precipitation.

Experiments in raindrop erosion led ELLISON [1944] to believe that most of the severe sheet erosion found at the tops of hummocks and hills and probably many of the erosional deposits along the bases of slopes are due to raindrop splash and not to surface flow.

COOK [1936] believed that raindrop velocity is one of the variables in the water erosion process and HORTON [1940] in considering the effects of rainfall intensity and drop size on infiltration regarded kinetic energy per inch of rain as the important property.

Although a great many measurements have been made to determine the influence of forest growth on the amount of precipitation reaching the forest soil, there have been few to determine the change in quality. In fact there apparently has been no quantitative information published on the size or velocity of raindrops under forest canopies although numerous writers have observed and recorded the fact that raindrops under forest stands are frequently much larger than the largest raindrops falling in the open. Since LAWS [1941] has shown that waterdrops at least up to six mm in diameter and probably drops of any size attain 95 per cent of maximum velocity after falling only 7.8 m, under many forest stands drops temporarily intercepted by the canopy must still attain a velocity at the time they reach ground level approximately equivalent to that of unchecked precipitation. It is not an unreasonable conclusion, therefore, that in some stands at least, the striking force of raindrops on the soil surface is greater than that of precipitation in the open. Obviously the presence of dense undergrowth would change this condition markedly.

Changes in the quality of precipitation that may decrease its erosive power include an extension of the time during which precipitation falls and a reduction in the striking force of that portion of rainfall that reaches the soil by running down branches and stems. Clearly the former condition is varied greatly by such factors as tree species, duration of rainfall, and wind velocity. Thus, STAHL [1893] described a European oak and apple, the American tulip poplar and several Australian trees as still retaining a part of the precipitation even against strong shaking more than an hour after rainfall; whereas most of the tropical species native to Java were almost entirely free of water after the same length of time.

The amount of water running down stems likewise varies with the species of tree, as well as such factors as the regularity of the crown and the angle of the branches. Many tropical species with smooth bark and long pointed leaves are especially well adapted for shedding water. In temperate zones, however, the amount of precipitation running down tree trunks, although varying considerably with species, is apparently much less important. The actual amounts measured have been found to vary over a considerable range, but ZON [1927] summarizes the situation by stating that the amount of precipitation reaching the ground along branches and trunks in a coniferous forest is very small (0.7-3.0 per cent), while in deciduous forests under average conditions it is about 15 per cent.

In the light of the preceding discussion it seems clear that at the present stage of knowledge of the influence of forest growth on precipitation it is impossible to evaluate definitely the importance of the forest growth as a protective agent against soil erosion. Before this can be done with safety, a great deal of information must be obtained concerning the qualitative changes in rainfall passing through tree canopies and also concerning the relative importance of such changes in the process of soil erosion.

Measuring raindrop size by the flour method--A number of methods have been suggested in the past for measuring raindrop size, but apparently the best is the flour method proposed by BENTLEY [1904] and later modified by LAWS and PARSONS [1943]. In brief, this method consists of exposing to the rain pans containing an inch deep layer of fine, uncompacted kitchen flour for a few seconds. The raindrops are left in the pan until the dough pellets that are invariably formed have hardened, and the latter are then separated from the flour and dried to constant weight in an oven at about 110°C. The weight of the raindrops can be computed from the weight of the oven dry dough pellets by using the relationship obtained in the following manner.

Drops are produced by allowing water to drip from glass tubes of various sizes, and the average drop mass for each tube is determined by counting and weighing a number of drops. Drops from each tube are also caught in pans of freshly sifted flour, weight determinations being made before and after the pans are exposed as a check to prove that drop size has remained constant. After the dough pellets have been separated from the flour, dried in the oven, weighed, and counted, the ratio which LAWS and PARSONS [1943] have called the "mass ratio" is computed for each drop size by dividing the average drop mass by the average pellet mass. A straight line relationship has been found to exist between mass ratio and pellet mass when the data is plotted on semi-logarithmic graph paper.

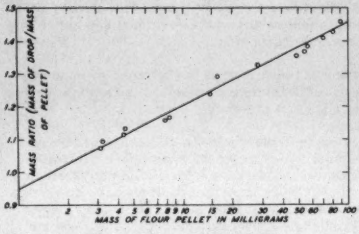

Fig. 1--Flour calibration

The results of the calibration of the flour used in this work are shown in Figure 1. Because of the great difficulty in forcing water to drip from the fine capillary tubes required to produce drops in the order of one mg or less and because of the far greater importance of large raindrops in the present study, it was decided to accept as a minimum value the smallest drop that could be produced without applying pressure to the tube (approximately three and one-third mg), and to estimate by extrapolation ratios below this point.

Influence of a red pine canopy on the characteristics of rainfall--A 29-year old red pine plantation near New Haven, Connecticut was chosen for studying the influence of tree canopies on the quality of rainfall partly because of its dense and completely closed canopy that might be expected to offer a maximum of protection to the soil and partly because of its proximity to an open field that made it possible for comparable samples of rainfall to be taken. The trees were spaced six feet by six feet and no mortality had occured. The lower limit of the living crowns averaged 28 ft above the ground and the average crown depth was 11 ft. Light measurements made under the tree canopy on July 15, 1947 at noon with a Weston illumination meter gave readings that averaged 13 per cent of full sunlight. The light flecks averaged 47 per cent and the dark shadows four per cent of full sunlight.

The procedure followed in sampling was to expose alternately under the red pine stand and in the open a total of ten pans of freshly sifted flour, the length of exposure being timed by stop watch and varying somewhat depending on the intensity of rainfall. The operation usually took about 15 min and only periods of rainfall that promised at least 15 min of steady rain without excessive wind were chosen for sampling. Minor fluctuations in intensity were taken care of by the fact that each of the final comparisons between open and forested conditions consisted of averages of the samples made alternately in each area.

Table 1--Average intensities of rainfall and average median drop sizes of samples taken in an open field and in a 29-year old red pine plantation during five rainstorms

Date of storm	Average intensity of rainfall		Median drop size	
	Open field	Under pine	Open field	Under pine
	in/hr	in/hr	mm	mm
May 27, 1947	0.09	0.09	0.74	3.52
June 2, 1947	0.13	0.15	1.35	3.37
June 2, 1947	0.22	0.22	1.23	2.83
Aug. 7, 1946	0.45	0.48	1.56	3.47
July 16, 1947	1.38	1.43	2.11	3.58

Since the scope of the work did not allow a study of rainfall differences throughout the whole course of a storm, the period of rainfall after the canopy had become thoroughly wet and before the rain in the open had abated was chosen for sampling. In all, five storms varying in intensity from 0.09 in/hr to 1.38 in/hr were studied, and the fact that in each case the average intensity of rainfall in the open was found to be about equal to that under the pine canopy (see Table 1) indicates that a similar period was sampled in each storm.

Median drop size--The system used for analyzing raindrop samples was similar to that described by LAWS and PARSONS [1943]. In brief, the oven dried flour pellets of each sample were separated into five size classes by screening through a stack of sieves. Each size class was weighed and counted to give the mass of the average pellet from which could be obtained, through use of the relationship between mass ratio and pellet mass, previously discussed, the mass of the average raindrop in each of the five categories. By assuming spherical drops, diameters of the average drops could be determined.

The percentages of total mass of the samples in each size class were next obtained, and from these values were calculated the cumulative volumes or the percentages of the total liquid volume of the samples falling in drops of the same size as and smaller than the average drop in each size category. By plotting cumulative volumes against average drop diameters, typical cumulative-frequency curves were constructed for each sample, and from these curves were read the median drop sizes.

Finally the individual median drop sizes in the open and under the pine canopy were averaged for each rain sampled and the average rainfall intensities (obtained by dividing the volume of all drops by the product of pan area and pan exposure) were likewise averaged. These resulting data are summarized in Table 1.

LAWS and PARSONS [1943], after sampling many storms in the open, concluded that a definite relationship exists between rainfall intensity and median drop size (the greater the intensity, the larger the drop size), but due to the small area of the pans and the extremely brief periods of exposure, individual samples can be expected to vary considerably. The relationship that Laws and Parsons noted is quite clearly shown by the part of the data in Table 1 that relates to rainfall in the open. Rainfall under the pine plantation, however, appears to be of a different character. The average median drops are much larger than comparable drops in the open even during heavy rainfall and the size appears to be relatively constant regardless of rainfall intensity.

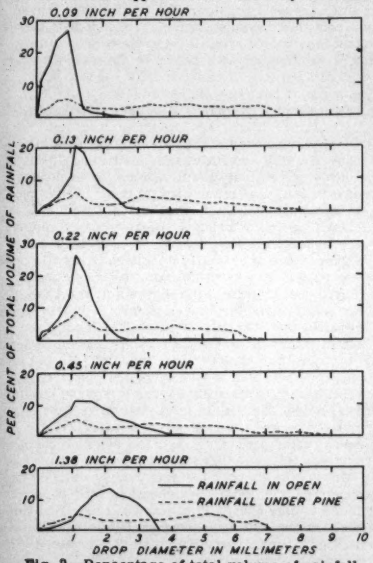
0.09 INCH PER HOUR
0.13 INCH PER HOUR
0.22 INCH PER HOUR
0.45 INCH PER HOUR
1.38 INCH PER HOUR
RAINFALL IN OPEN
RAINFALL UNDER PINE
PER CENT OF TOTAL VOLUME OF RAINFALL
DROP DIAMETER IN MILLIMETERS

Fig. 2--Percentage of total volume of rainfall contributed by drops of various sizes

Size distribution of raindrops--Cumulative volume percentages were read from the cumulative volume curves for each sample of rainfall for drop sizes varying by intervals of 0.25 mm and these values were then averaged for each storm according to the place of sampling (in the open or under pine). The percentage of the total volume within each 0.25 mm interval was then computed for each storm from the averages of each group which resulted in the size distribution data shown graphically in Figure 2.

LAWS and PARSONS [1943] found a considerable variation in volume-frequency curves for samples taken during rainfalls of equal intensity. By averaging the results of many samples, however, they were able to produce smooth curves that indicate changes in the character of rainfall in the open correlated with changing intensity. Although all of the volume percentage data when plotted against drop size resulted in typical bell-shaped frequency curves, it was found that during light rains the range of drop size is small and the mode is small. As the rainfall intensity increases, the range in drop size expands greatly and the mode likewise increases. During intense rains drops as large as seven mm occur but these make up only a very small percentage of the total volume of rain falling.

The volume-frequency curves for the five storms sampled in this study (see Fig. 2), being averages of only a small number of samples in each case, are somewhat erratic although those representing rainfall in the open quite definitely show the same general features as the smooth curves of Laws and Parsons. Rainfall under the pine canopy, however, is obviously different in character from that falling in the open. The most noticeable feature of these curves is their flatness which indicates the tendency for more or less equal distribution by volume of rain among drops of all sizes. Thus under a pine canopy not only do drops reach greater proportions than in the open but also a much greater percentage of the total volume of water falls in the form of large drops. Furthermore the distribution curves indicate that the intensity of rainfall, within the range measured, has little effect on size characteristics

of raindrops under the pine canopy. Although during heavy rainfalls a greater volume of water is falling under the pine, its breakdown into drops of various sizes is apparently comparable to that of light rains.

Kinetic energy of rainfall--In spite of the differences observed in the volume distribution of rainfall according to drop size classes between uninterrupted precipitation and that which has passed through a pine canopy, the question yet remains whether raindrops under the pine canopy may not even so strike the soil with less force because of their much shorter distance of fall than those in the open. It is the striking force or kinetic energy of the rain that may damage soil structure and this value depends not only on the mass of the rain drops but also on their velocity. $KE = mV^2/2$; where KE is kinetic energy in foot pounds, m is mass in slugs, and V is velocity in ft/sec.

Fortunately LAWS [1941] has made available information conerning the velocities of free falling water drops of different sizes in calm air after falls of varying distances. By making use of these data and of the raindrop distribution data previously discussed, and by assuming that all drops under the pine originate from the base of the living crown which in this case is 28 ft above the ground, it is possible to derive an estimate of the striking force per sq ft of soil surface for each inch of rain falling at the intensities sampled both in the open and under pine for five rainfalls. These data are shown graphically in Figure 3 and prove quite conclusively that throughout the range sampled the striking force of the rain under this canopy is considerably greater than that in the open. It is true, however, as might be expected from the previous discussion of raindrop distribution that the force under pine tends to be constant per inch of rainfall regardless of the intensity, whereas in the open, because of the greater proportion of water falling in the form of large sized drops during heavy rainfalls, the kinetic energy of each inch of rain per sq ft of soil surface increases as the intensity increases. Thus, during very heavy rainfalls the force of the rain under the pine canopy may be equalled or in some cases surpassed by that of uninterrupted rain.

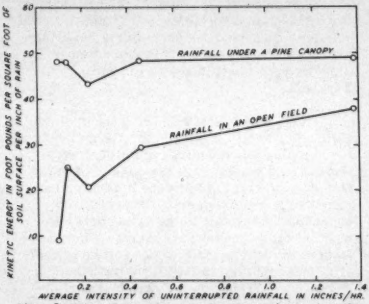

Fig. 3--Kinetic energy per square foot of soil surface for one inch of rainfall

By using the average volume-distribution data of LAWS and PARSONS [1943], the kinetic energy per sq foot of soil surface for each inch of rain falling at intensities up to six inches per hour can be computed. If it is assumed that the kinetic energy of rainfall under the pine canopy per inch of rain remains the same through the higher range of rainfall intensities (a not illogical supposition in view of the fact that drops probably do not drip from the leaves and branches of the canopy until they have reached a certain size regardless of the rate at which they form), an estimate can be made of the rate of precipitation necessary before the impact force of rain in the open is equivalent to that under the pine. This relationship is shown in Figure 4 from which it can be seen that rainfalls of intensities less that two inches per hour possess more kinetic energy after passing through the red pine canopy that was tested in this study than when falling on a bare field; whereas at intensities greater than two inches per hour the pine canopy reduces the impact force to some extent. Since only a small percentage of rainfall in Connecticut falls at rates in excess of two inches per hour, it is doubtful whether the pine canopy is of practical significance in reducing the total seasonal impact caused by rainfall on the land. It is very probable that the increased impact that occurs under the canopy during light storms more than offsets decreases in impact that the canopy may cause during heavy storms.

Summary and conclusions--Samples of rainfall were taken during five storms varying in intensity from 0.09 in/hr to 1.38 in/hr by means of the flour method of sampling in a 29-year old red pine plantation and in an adjacent open field in order to measure the effects of a dense tree canopy on the distribution of rainfall by drop size classes and on its striking force at the soil surface. Measurements were made during the period in each storm after the canopy had become thoroughly wet, at which time it was found that the volumes of water striking the soil per sq ft/hr in the pine plantation and in the open were approximately equal. The following differences in the characteristics of rainfall were noted:

(1) Median drop size in the open field increases with increasing rate of rainfall. Under the pine canopy, however, the median drop diameter apparently is unrelated to precipitation rate within the range of rainfall rates measured.

(2) The volume distribution of uninterrupted rainfall by drop diameter classes produces bell-shaped frequency curves that bear the same relation to rainfall intensity that was reported previously by LAWS and PARSONS [1943]; namely, during light rainfalls a large proportion of the volume falls in the form of small drops and the range in drop size is also small, but at higher intensities the modal drops are larger. Comparable distribution curves for precipitation under the pine canopy, however, are markedly different. At all rates of precipitation measured these curves show a considerably greater range in drop size and furthermore their flatness indicates a more uniform distribution of volume of water throughout the range in drop size. The volume distribution of rainfall by drop diameter classes under the pine canopy appears to be little affected by rate of precipitation.

(3) Throughout the range of precipitation rates sampled, the kinetic energy of rainfall for each inch of rain per sq ft of soil surface is considerably greater under the pine canopy than in the open. Whereas the striking force of rain under the pine apparently remains unchanged as the rate of precipitation increases, that of rain in the open bears a positive relation to rainfall intensity.

(4) By using average volume distribution data obtained by LAWS and PARSONS [1943] from which to compute values of kinetic energy of rainfall at high rates of precipitation, and by assuming that the kinetic energy of rain under the pine canopy remains constant at these high rates of precipitation, it can be estimated that for rates up to two in/hr the striking force of uninterrupted rain is less than that which passes through the pine canopy. At rates exceeding two in/hr the pine canopy reduces slightly the striking force of the rain although even at a rate of six inches per hour the kinetic energy of rain under the pine by this method of estimation is only about 13 per cent less than that of uninterrupted rainfall.

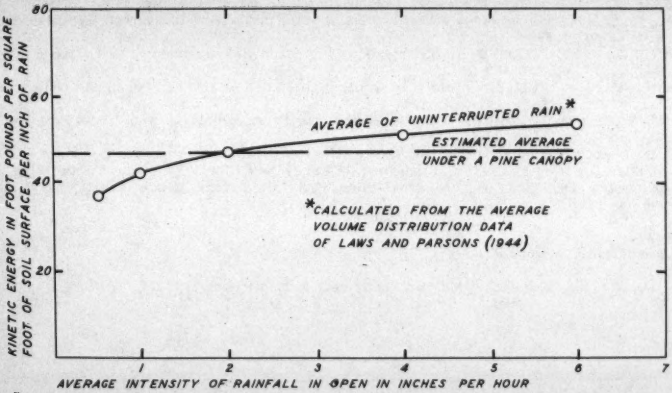

Fig. 4--Average kinetic energy of uninterrupted rainfall at varying rates of precipitation

It seems safe to conclude that for rates of precipitation commonly experienced in Connecticut the dense canopy of a red pine plantation the base of which is at least 28 ft above the soil surface provides no protection to the soil by breaking the force of the rain. Admittedly the condition is altered if a dense understory should be present, for the precipitation is then interrupted once more and does not attain a sufficient velocity before striking the soil to build up kinetic energy equal to that of uninterrupted rainfall. This fact might be used as an argument for maintaining uneven aged stands wherever the soil is not protected by a sufficiently thick litter layer.

The protection afforded the mineral soil under forest stands against compaction and breakdown of aggregates by rainfall arises not from the overhead canopy breaking the impact of the raindrops but rather from the presence of a layer or layers of unincorporated organic matter on the mineral soil surface. As mentioned above, a luxurient growth of shrubby or herbaceous vegetation also

serves the same purpose. It may be suggested that the frequently reported deterioration in physical properties of forest soils resulting from litter removal in European countries is related in no small measure to damage by rainfall impact.

In view of the fact that few canopies are more dense it might be expected that a red pine plantation should be more efficient than most other forest types in breaking the force of the rain. As has been shown, however, the mere interruption of rainfall does not protect the soil provided the canopy is sufficiently high above the ground. The question depends instead on the size of the rain drops falling from the canopy. Whether forest species other than red pine have a similar effect on the size distribution of rain drops can not be stated without further evidence although it seems logical to predict that such may be the case.

Acknowledgments--Acknowledgment is made to H. J. Lutz of the Yale School of Forestry and to W. D. Ellison of the Soil Conservation Service for their very helpful suggestions and criticisms.

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THE CHARACTERISTICS OF WIND WAVES ON LAKES AND PROTECTED BAYS

J. W. Johnson

Abstract--The results of investigations to determine the height and period of waves generated by wind blowing over lakes, reservoirs, or bays, protected from ocean swell, are given. Some information is presented on the variability of wave length and crest length as a function of fetch in the generating area. Recommendations are made for further investigations which are needed to adequately define the relationships between wave characteristics and wind velocity.

Introduction--Basic information on the characteristics of waves generated by wind blowing over a limited fetch is necessary in many engineering and operational problems. Examples of a few of these problems are: The design of harbor facilities and shore protection works on land-locked bays and lakes; the design of the face of earth-fill dams on reservoirs for protection against wave wash; and the operation of seaplanes from bays, lakes, and other areas not exposed to swell from the open sea. The basic theory of wave generation has been developed previously [SVERDRUP and MUNK, 1947]. Certain relationships between wave and wind characteristics also have been developed [HYDROGRAPHIC OFFICE, 1945]; however, because much of the data used in establishing these relationships were obtained from observations in the open sea, or relatively large lakes, it appeared desirable that data should be obtained for those conditions where the fetch is relatively short. To supply preliminary information in connection with this problem observations of wave and wind characteristics were made at Clear Lake, California by the Department of Engineering, University of California, as part of an extensive investigation on surface waves for the Bureau of Ships of the United States Navy. This paper which is preliminary in character summarizes the data obtained to date and is intended to serve as a guide to future investigations that are needed to define completely the relationships between wind and waves.

Model law for wave generation--The principal assumptions underlying the theory of the generation of waves in deep water are: (1) The wave motion is controlled by gravity and is not affected by viscosity or surface tension. (2) Normal and tangential forces exerted on the water surface by the wind are proportional to the squares of velocities or velocity differences.

These are the assumptions underlying the model laws for the motion of a frictionless fluid under the action of gravity. Using the model laws to discover dynamically similar conditions of fetch, duration of wind, wind speed, wave height, and wave period should simplify the analysis and presentation of observations. The following symbols will be used in the discussion to follow: F, fetch or distance along which the propagation of the wave is continued, ft; X, fraction of total fetch, ft; H, wave height, ft; L, wave length, ft; T, wave period, sec; U, wind speed, ft/sec; t, actual duration of wind, sec; and t_m, minimum duration time required to raise the highest wave for a given fetch.

Assuming that a particular fetch might be considered a model of every other fetch, dynamical similarity between two fetches of different lengths is achieved when the wave heights and lengths at corresponding fractions of the total fetch, X/F, are in the same linear ratio as the fetches themselves. The dynamical problem is to discover the corresponding scale ratios of speeds and periods. Thus

$$\text{Scale of lengths} = R_L = L_2/L_1 = H_2/H_1 = F_2/F_1$$

$$\text{Scale of speeds} = R_v = C_2/C_1 = U_2/U_1$$

$$\text{Scale of time intervals} = R_T = t_2/t_1 = T_2/T_1$$

The equation relating wave velocity and wave length may be utilized to relate these ratios; that is

$$C^2 = gL/2\pi$$

$$(C_2/C_1)^2 = L_2/L_1$$

or

$$R_V^2 = R_L$$

but since

$$L = CT$$

$$L_2/L_1 = (C_2/C_1)(T_2/T_1)$$

$$R_L = R_V \cdot R_T = R_V^2$$

therefore

$$R_T = R_V$$

The variables involved in the generation of waves are H, L, U, F, and t. Taking U as the principal independent variable, a method of plotting observations is obtained as follows

$$R_T/R_V = 1 = (t_2/t_1)/U_2/U_1) = (t_2/U_2)/(t_1/U_1)$$

$$R_L/R_V^2 = 1 = (X_2/X_1)/(U_2^2/U_1^2) = (X_2/U_2^2)/(X_1/U_1^2)$$

$$= (L_2/L_1)/(U_2^2/U_1^2) = (L_2/U_2^2)/(L_1/U_1^2)$$

$$= (H_2/H_1)/(U_2^2/U_1^2) = (H_2/U_2^2)/(H_1/U_1^2)$$

These equations state that these ratios should have the same values at dynamically similar points. For example, if H_1 and L_1 are measured at F_1, t_1, and U_1, the corresponding quantities at speed U_2 are

$$H_2 = H_1 \ (U_2/U_1)^2$$

$$L_2 = L_1 \ (U_2/U_1)^2$$

$$F_2 = F_1 \ (U_2/U_1)^2$$

$$t_2 = t_1 \ (U_2/U_1)$$

Observed data on wave and wind characteristics should reduce to two diagrams, one representing wave height and the other wave length (or period), if H/U^2 and L/U^2 (or T/U) are plotted as functions of t/U and F/U^2. In the growth of wind waves, one of the important factors is the time required by a wind of a given velocity to raise the highest possible waves at the end of a given fetch. This time factor will be designated hereafter as the minimum duration (t_m) of the wind. The significance of this term is that if the duration of the wind exceeds this time, the maximum wave height attained is controlled by the length of the fetch. Should the wind prevail for a time which is less than this value, then the maximum height is controlled by the actual duration of the wind. To obtain information on the appearance of such plots and the order of magnitude of the variables, revised data from the publication Wind Waves and Swell [HYDROGRAPHIC OFFICE, 1945] have been used and are shown in Figure 1, wherein the terms H/U^2 and L/U^2 are presented as functions of t/U and F/U^2. In this figure the term T/U is used instead of its equivalent, L/U^2, since the wave period T (where $T = \sqrt{L/5.12}$ for deep water waves) is easier to measure than the wave length, L. The diagrams in Figure 1 may be used in estimating wave conditions from wind data as follows: For a particular fetch, F, over which a wind velocity, U, is blowing, the value of F/U^2 is computed and the diagram is entered and the minimum duration time, t_m, determined from the term t_m/U. If the actual duration of the wind exceeds this minimum duration time, then fetch controls the maximum wave height, and the wave height is determined from the curve which shows the relationship between F/U^2 and H/U^2. On the other hand, if the actual duration time of the wind is less than the minimum duration time as determined above, then the wave height would be determined by the relationship between t/U and H/U^2. The period in a particular case would be obtained from either the curve which shows the relationship between T/U and F/U^2 or between T/U and t/U, depending on whether the fetch or the wind duration is the control. It should be noted that the terms in Figure 1 can be made dimensionless by multiplying by g, the acceleration of gravity.

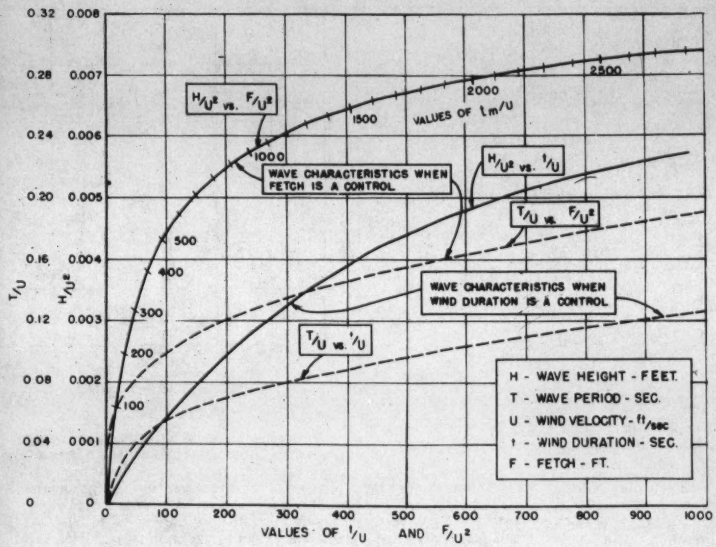
H/U² vs. F/U²
VALUES OF t m/U
WAVE CHARACTERISTICS WHEN FETCH IS A CONTROL
H/U² vs. t/U
T/U vs. F/U²
WAVE CHARACTERISTICS WHEN WIND DURATION IS A CONTROL
T/U vs. t/U
H - WAVE HEIGHT - FEET.
T - WAVE PERIOD - SEC.
U - WIND VELOCITY - ft/sec
t - WIND DURATION - SEC.
F - FETCH - FT.
T/U
H/U²
VALUES OF t/U AND F/U²

Fig. 1--Relationship between wave height, wave period, fetch, wind velocity, and wind duration

Experimental data--To provide experimental data on the generation of waves by wind observations were made at Clear Lake, California on two occasions, first in December 1944 and then later in the spring of 1946. In the first tests the plan was that wind velocity would be measured with an anemometer on shore, and wave heights would be measured by photographing the waves against a grid from a DUKW which moved from point to point along the fetch. It was planned also to obtain vertical overlapping photographs of the waves from a plane flying along the fetch. Such photographs would be of value in giving information on the variation of wave length and length of crest with distance along the fetch.

During the period of these observations conditions were suitable for only one plane flight. On this ocassion three passes by the plane were made along the approximate fetch at altitudes of 1000, 2000, and 3000 ft. Wave-height observations were made from a DUKW at the approximate center of the flight. Wind velocity was obtained by anemometers at two stations, one located on land at the northerly end of the lake and another located on the DUKW.

Figure 2 shows that portion of Clear Lake in which the experiments were made. Indicated are the locations of the shore anemometer station and the flight line for the flight made at an elevation of 3000 ft. The small circles along the flight line are the locations of the centers of photographs for which data are summarized below. Because the flight line was not parallel to the direction of wave travel, it was necessary to orient the various photographs with respect to the shoreline and then scale the length of the fetch for each photograph from a map of the the lake.

A summary of the wind data for the north station on December 2, 1944 is shown in Figure 3. A comparison of the wind data taken at the shore station and at the DUKW showed that considerable variation in velocity and direction probably occurred over the lake, a condition caused no doubt by the relatively high topography surrounding the lake. Another item of importance is that consideration of the observed wind data in connection with Figure 1 shows that the wave height and period probably were controlled by duration, rather than by fetch.

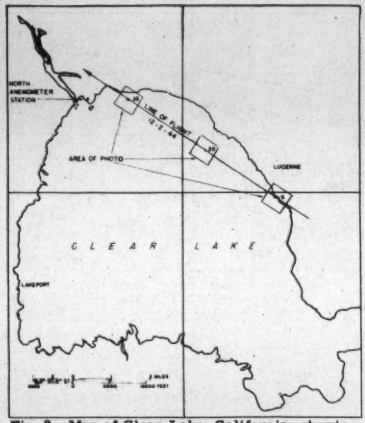

Fig. 2--Map of Clear Lake, California, showing locations at which wave and wind measurements were made

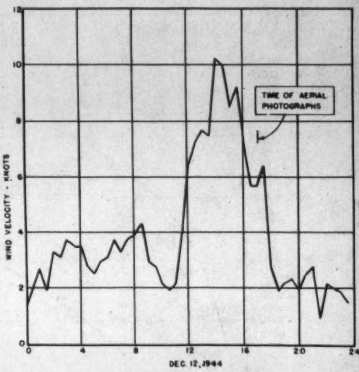

Fig. 3--Summary of wind data for the north station

Perhaps the most useful data resulting from these first observations was information from the aerial photographs on the variability of waves along a fetch. As an illustration of the character of the water surface in a generating area the aerial photograph shown in Figure 4 is typical. Ten photographs were selected along the line of flight and were analyzed for wave length and for length along the crest. In this analysis the wave length measurements indirectly gave information on the variation of wave period with length of fetch. On each of the ten photographs a piece of acetate was placed over the photograph and every well defined wave crest on five arbitrary parallel ranges near the center of photograph was scratched on the acetate. Measurement of wave length then was made by a combination magnigying glass and scale. In the case of length along the crest every crest visible in a two-inch square near the center of a photograph was scratched on an acetate overlay and its length then was measured. These data were tabulated and a statistical summary was made of the two terms and summarized in the form of frequency distributions as illustrated by Figures 5 and 6. Figure 5 shows frequency distributions of wave length, and Figure 6 shows frequency distributions of crest length obtained from photographs at the beginning, center, and end of the flight. Indicated on each of these diagrams are the mean wave and crest lengths of all waves, the mean wave and crest lengths of the longest 30 per cent, and the number of measurements utilized in the analysis. The mean of the longest 30 per cent of the waves is included to give general information on the length of the longer waves that were present. The 30 per cent value was chosen because these waves have been considered to be the most significant waves present at any one time in a given area [HYDROGRAPHIC OFFICE, 1945]. A plot of the data on mean wave length and the mean wave length of the longest 30 per cent as a function of the fetch is shown in Figure 7b. A similar plot for the data on length along the crest is shown in Figure 7c. Examination of these plots shows that both the wave length and length along the crest increase with fetch.

To supplement the frequency distributions, as illustrated by the diagrams in Figures 5 and 6, the standard deviation of the mean was computed by the formula:

$$\sigma_m = \sqrt{\Sigma p^2/n}$$

where σ_m is the standard deviation of the mean; p is the deviation of an observed value from the arithmetic mean of the observed values; and n is the number of observations

The values of standard deviation give a measure of dispersion of the observations; that is, in a normal distribution, 68.3 per cent of the observations fall within range of σ_m on either side of the arithmetic mean, and 95.4 per cent of the observations fall within a range of $2\sigma_m$. To indicate the variation of the dispersion of the observations along the fetch, the standard deviation for wave length was plotted as a function of fetch. The relationship between σ_m and fetch for wave

Fig. 4--Aerial photo showing the typical appearance of waves in a generating area; note variability in wave length and in crest length (U. S. Navy Photo)

length is rather well defined and is shown in Figure 7a. The plot for crest length is not shown, since considerable scatter occurred, but the general trend was an increase in standard deviation with fetch.

In addition to the data on wave characteristics from the aerial photographs taken on December 1944, observations of wave heights and periods were made from the DUKW at an offshore point. Wave heights were obtained by the use of a grid board, and wave period was taken as the average of several measurements of the time of passage of ten consecutive waves past a fixed point. Because the wind appeared to be continuously changing (see Fig. 3), no attempt was made to correlate these visual observations or the data from Figure 7b, with Figure 1.

For the tests made in March and April 1946, two observation stations were established at Clear Lake. At the north end of the lake (see Fig. 2) a recording anemometer and a wind direction indicator were established at an elevation of 25 ft above the lake surface. At Lucerne observations were made on both wave and wind characteristics. Wind velocity was obtained from a cup anemometer at an elevation of about 15 ft above the water surface. Wind direction was obtained by taking a compass bearing of the direction indicated by a wind vane. Observations on wave

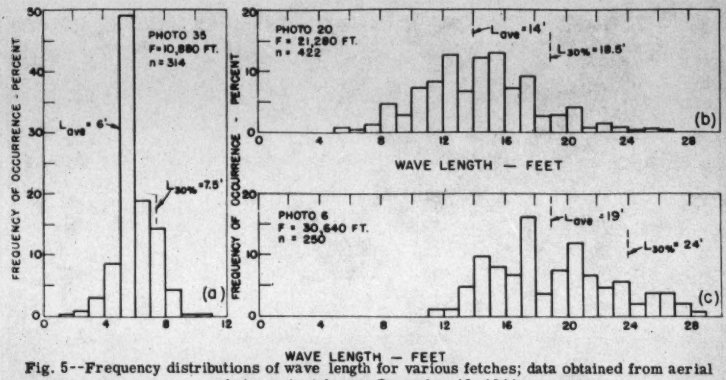

Fig. 5--Frequency distributions of wave length for various fetches; data obtained from aerial photographs taken on December 12, 1944

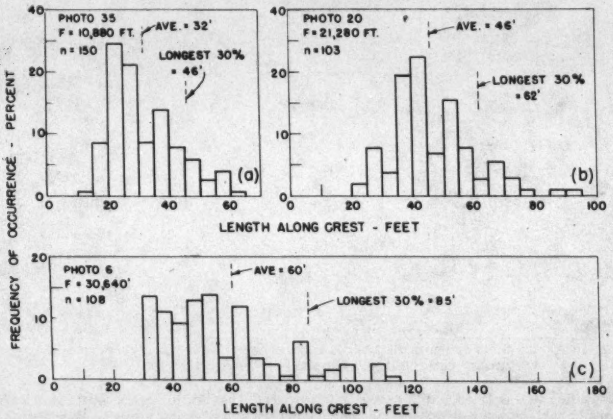

Fig. 6--Frequency distributions of crest length for various fetches; data obtained from aerial photographs taken on December 12, 1944

characteristics were made both visually and by a pressure recorder. The visual observations were made of wave height and period against a graduated pole attached to a pile in about seven ft of water. The wave recorder, from which height and period could be determined, was located on a pile with the pressure unit at 18 inches below the still-water surface in water seven ft deep. The recorder was located in a shelter on shore where electricity was avilable for its operation.

Observations of the various data were taken whenever waves existed on the lake. The wind recorder at the north end of the lake operated continuously. The visual observations of wind and wave characteristics were made at half-hour intervals as long as waves existed on the lake. The wave recorder was operated for an eight-min period at the beginning of each half-hour interval. Figure 8 shows a sample of the recorder chart. This record is of interest since it gives a typical example of the sequence of the height and period usually found in wind generated waves.

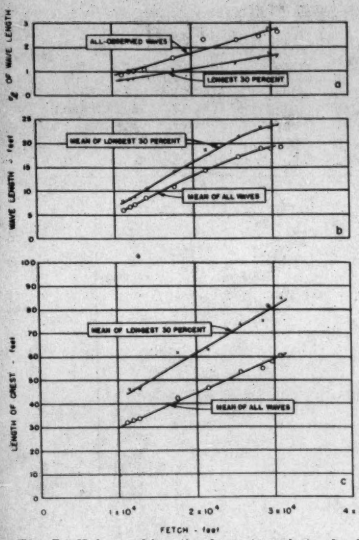

Fig. 7--Values of length of crest, and standard deviation of wave length as a function of fetch; data obtained from aerial photographs of December 12, 1944

The first step in the reduction of the various data was to summarize in graphical form the values of wind velocity, wave height, and wave period as a function of time. Wave height as determined from the recorder charts was taken as the average of the highest 30 per cent of the waves present. The average wave height as obtained by visual observation probably would represent an even smaller percentage of the highest waves. The various data were summarized, as illustrated in Figure 9, for the days on which waves existed on the lake. From the wind direction observed at Lucerne the probable fetch was scaled from a map; however, such values of fetch may be in error due to differences in wind direction over various parts of the lake. Also the wind velocity as observed at Lucerne was sometimes as much as 20 per cent higher than that at the north station.

Relationship between wind and wave characteristics--The various data on wind and wave characteristics were critically examined to supply data to define better the curves presented in Figure 1. The Clear Lake data obtained on December 2, 1944 appear too limited to utilize in determining the relationship between wind and waves; although the results obtained from the aerial photographs on the day give valuable information on the variability of wave length and crest length along the fetch. These results were discussed above and are summarized in Figure 7.

The data obtained during the April 1946 studies give some information on the relationship between the waves and the wind. To use these data it was necessary to resort to certain averaging methods. For the curves of recorded wave height and wave period moving averages were computed and plotted as illustrated in Figure 9. These moving average curves then were examined for conditions when a fairly constant wind speed (at the north anemometer station) appeared to prevail. Six such instances were selected. For the data shown in Figure 9 the averages of wind velocity, wave height, and wave period are indicated. For all six instances, these data and the computed terms H/U^2, T/U, and $F/U2$, are summarized in Table 1. Also included in this table are an estimated wind duration, the calculated term t/U, and the minimum duration, t_m/U. Values of this latter term were obtained from Figure 1 for the corresponding values of F/U^2. Comparison of the last two columns in Table 1 indicates that wind duration, and not fetch, probably was the controlling factor in all of these observations.

Plots of the data in Table 1 appear in Figure 10. In Figure 10b values of T/U are plotted against values of both t/U and F/U^2, whereas plots of $H/U2$ and these same variable are shown in Figure 10a. In both of these figures the Hydrographic Office curves are shown for comparative purposes [HYDROGRAPHIC OFFICE, 1945]. Although these data are too few to form any conclusions, it is noted that the wave periods from the Clear Lake data are greater than those given by the Hydrographic Office curves for either the fetch or duration controls. On the other hand, data on wave height (see Fig. 10a) scatter about the duration control curve as might be expected from the last column of Table 1 which indicates that duration probably is the controlling factor.

Other data that may be compared with the Clear Lake observations are the results of flume studies made at the University of Minnesota [FLINSCH, 1946] and in England [STANTON, MARSHALL and HOUGHTON, 1932]. Both sets of observations were made by forcing air through a covered flume and measuring the wind velocity, wave length, wave period, and in some instances the wave height. Examination of the various data shows that in some of the experimental runs the waves were in the capillary range; that is, the wave period was 0.27 sec or less. This division between capillary and gravity waves is purely arbitrary and is taken as that period at which the wave velocity by the capillary wave equation differs by one per cent from the value of velocity computed by the gravity wave equation.

Table 1--Summary of Clear Lake data on wind generated waves

Date	H	T	F	U	t	H/U^2	T/U	F/U^2	t/U	t_m/U
1946	ft	sec	ft	ft/sec	sec					
Apr. 7	0.15	1.64	25,400	7.9	3600	0.0024	0.208	410	455	1500
Apr. 7	0.4	2.1	24,300	10.3	1800	0.0038	0.204	230	175	980
Apr. 8	0.5	2.0	24,500	14.2	6840	0.0025	0.141	121	480	600
Apr. 9	0.35	1.9	24,500	13.8	3600	0.0018	0.138	129	261	650
Apr. 12	0.55	2.1	21,600	14	5400	0.0028	0.150	110	386	570
Apr. 19	0.3	2.06	21,600	13	3600	0.0018	0.159	128	277	650

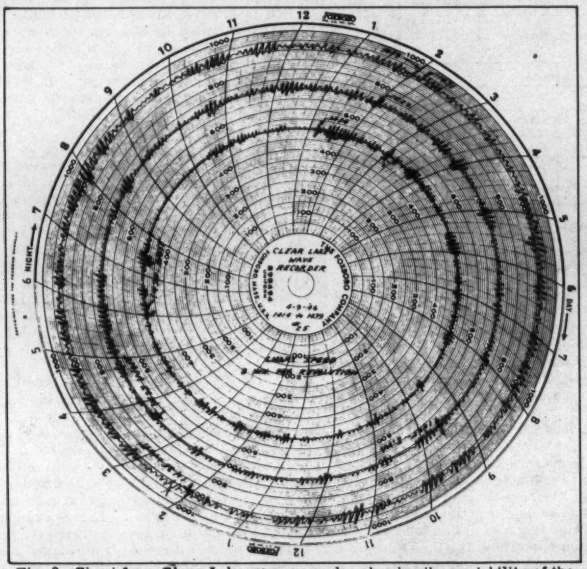

Fig. 8--Chart from Clear Lake wave recorder showing the variability of the height and period of waves with time

The data of Flinsch and Stanton, along with the Clear Lake results, have been plotted in Figure 11. In Figure 11a values of T/U have been plotted against values of F/U^2, and in Figure 11b values of H/U^2 have been plotted against F/U^2. In both diagrams the Hydrographic Office curves from Figure 1 have been plotted for comparative purposes. As previously noted in the plots appearing in Figure 10, the Clear Lake data fall above the Hydrographic Office curves for wave period and below for wave heights, a fact in the latter case which might be expected if the wind duration was below the minimum required to raise waves to their maximum height. Another factor in connection with the Clear Lake data which must be recognized is that the wind speed and direction probably varied considerably over the lake. It should be noted also in connection with the flume experiments discussed above that the wind speed in Flinsch's experiments was measured at 4.6 cm above the still-water level in the flume; whereas, in the Stanton experiments the speed was measured at nine cm above the still-water level. To properly correlate all of the various data the elevation of the point where the wind speed is measured should enter the model laws. The data of Flinsch, Stanton, and from Clear Lake were obtained with fresh water, whereas the Hydrographic Office curves were obtained from observations in the ocean. A correction due to the difference in water density theoretically should be made in attempting to correlate the data. Actually, this correction is probably small compared to experimental errors.

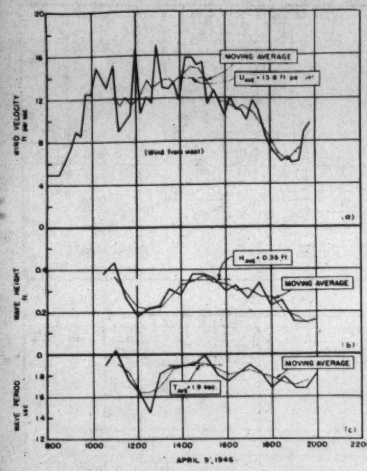

Fig. 9--Values of wind velocity, wave height, and wave period observed on April 9, 1946, at Clear Lake; moving averages and an average value for a steady-state condition are indicated for each variable

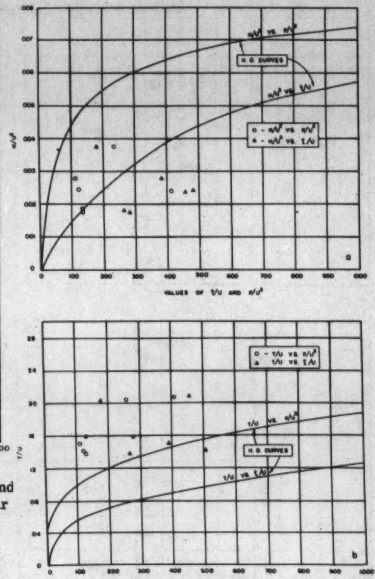

Fig. 10--Wave height and period as related to wind velocity and duration; Clear Lake data compared with data of HYDROGRAPHIC OFFICE [1945]

Conclusions and recommendations--The various data discussed above give valuable qualitative information on the generation of waves by wind blowing over short fetches, but considerably more observations are required to completely define the relationships between wind velocity, wind duration, fetch, wave height, and wave period. Such data should be obtained both from field investigations and from flume experiments. Locations for field investigations should be carefully selected such that wind direction and velocity over the fetch are not influenced by the surrounding topography. If possible, wind direction and velocity should be measured at several localities over the fetch. Wind velocity at several elevations over water should be observed at one location. Water depths should be sufficient to insure that only deep-water waves will exist; however, flat beaches should exist at the shore to prevent wave reflections from influencing the results. It is desirable that continuous recordings of all factors be made, but they should be supplemented by visual observations of wave height and period when possible. Both aerial and surface photographs of the waves on frequent occasions are highly desirable.

Flume experiments should be designed so that only gravity waves will exist over most of the fetch. If a wave period of 0.27 sec is taken as the lower limit in order to insure gravity waves, a selection may be made of flume length and wind speed. For example, suppose that the wave characteristics are to be investigated for the prototype conditions, F_p = 10 mi and U_p = 40 mph; then

$$F_p/U_p^2 = (10)(5280)/[(40)(5280/3600)]^2 = 15.4$$

Utilizing Figure 11 as a basis for design, the value of T_p/U_p corresponding to the above values of F_p/U_p^2 is 0.06. For this same value of T/U to exist in the model (where T_m = 0.27), the wind velocity would have to be 4.5 ft/sec and the fetch 311 ft. Further, for a fetch of ten mi and wind velocity of only five mi/hr (F/U^2 = 980) a flume of 2090 ft would be required to determine the relationship between wind and wave characteristics. It is of importance to recognize that these

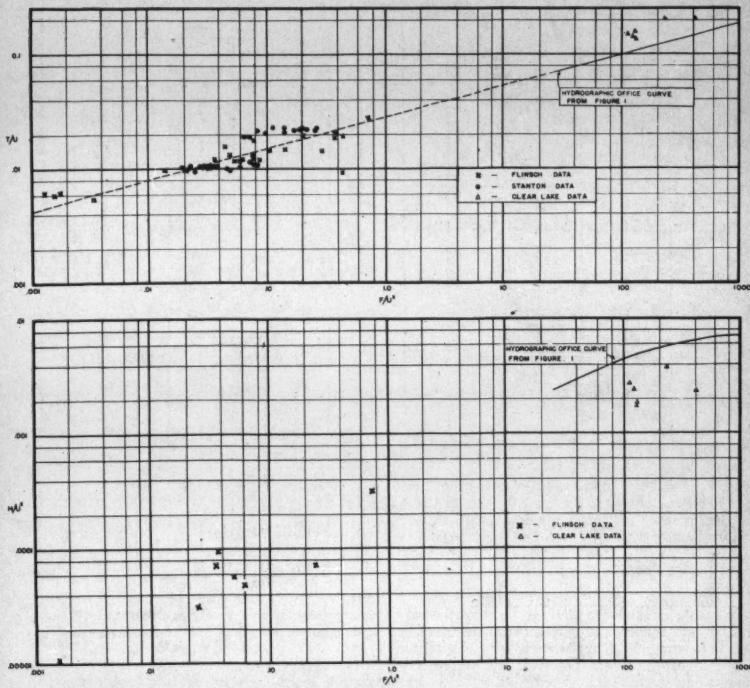

Fig. 11A and B--Relationship between windspeed, fetch, wave height, and wave period

values are the minimum length of flume, since the wave period would be 0.27 sec only near the end of the flume. The waves in the remaining part of the flume would have a period of less than this value.

In the majority of reservoirs the usual length of fetch and range in wind velocities are such that the value of F/U^2 probably will be less than 1000. A consideration of the above calculations indicates that to cover the range of values of F/U^2 up to approximately 1000, a flume over 2000 ft would be required to insure that gravity waves exist. However, to cover the range of F/U^2 up to a value of about 12 (prototype conditions: F = ten mi, U = 45 mph), a flume approximately 300 ft in length could be used with wind speeds of five ft/sec and greater. For a flume of this length it is important to investigate the proportion of the flume length required for waves of the minimum period of 0.27 sec to develop. Analysis shows that for wind velocities of five, 15, and 25 ft/sec lengths of 275, 45, and 19 ft, respectively, would be required. These computations show that for the lower wind speeds, such as five ft/sec, capillary waves prevail over most of the flume. It may be possible, however, that a detergent could be added to the water to reduce surface tension forces and thereby permit the use of shorter period waves (and shorter flumes) in the investigations.

As mentioned in the introduction, the contents of this report are preliminary in character and are intended as a guide to further experiments. It is hoped that in the future investigations in both the field and laboratory will be made to better define the relationships discussed above. Flume studies appear the most promising in giving details on the generation of waves by wind; however, such studies should be supplemented by observations in the field to cover the greatest possible range of the variables.

Acknowledgments--The work summarized in this paper was part of an extensive investigation on waves and surf for the Oceanographic Section, Bureau of Ships, United States Navy. M. P. O'Brien, Professor of Engineering, was in charge of the work at the University of California, and Roger Revelle was in charge of the Oceanographic Section. Grateful acknowledgment is made to B. F. Morey, Jr. for the extensive work involved in the analysis of the aerial photographs which constitutes a large portion of this paper.

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A REPRESENTATIVE PERIOD FOR A WATER-SUPPLY STUDY

Leonard L. Longacre

Abstract--In an engineering investigation requiring the use of water-supply records it is essential that the study shall cover a period that will be representative of long time conditions. This paper gives an outline of the analysis used in selecting the 30-year period 1906-1935 as typical of a long-time water supply for a study of hydro-power developments in the upper San Joaquin River Basin. A method used to extend a short record of runoff to cover the 30-year period is briefly described.

Introduction--Engineering studies requiring a knowledge of the water supply in a particular area must of necessity be based on historic records. It is necessary that the period adopted for the study be representative of conditions which may be expected to occur. A study of precipitation and runoff records clearly bring out that these phenomena occur in cycles (cycles being used in a very general sense), in which a series of years will occur with the general average above normal followed by a series of years with the average below normal. One or more years in a series may show a reversal of trend from the average of the series.

When water-supply data are required at locations where runoff records are available for only a few years, it is essential that a runoff record be obtained at some other location having similar hydrologic characteristics where records have been kept for a period sufficient to determine long-time trends. This longer record may be used as a base in expanding the short-time records at other locations.

Runoff is the residual of precipitation resulting from the cumulative effects of the characteristics of the drainage area and has long-time trends similar to precipitation. Precipitation records in many localities are available for much longer periods than runoff records and are valuable in checking on the long-time trends. Annual flows have greater variations from the long-time mean than annual precipitation, due largely to the residual nature of runoff.

The residual mass diagram [CALIFORNIA DEPARTMENT OF PUBLIC WORKS, 1923, p. 68] has been found to be a useful device in the study of long-time trends. The diagram is constructed by adding algebraically in chronological order the departures in per cent above or below 100 per cent that each year's value is of the annual mean for the adopted base period; the beginning and end of the base period will be at zero departure. The slope of the line upward toward the right indicates the per cent above the annual mean of the base period for that particular period while a downward slope indicates the percentage below the mean.

Determining the representative period--In Figure 1 is shown the residual mass diagram for the reconstructed natural runoff of the San Joaquin River near Friant, tabulated in Table 1. Water is now stored and regulated at six reservoirs above the Friant Station. The diagram was constructed using a base period of 54 years, 1890-1943; the period for which the reconstructed natural flow was available from the tabulation of the California State Division of Water Resources. The natural flows for the 1944 and 1945 seasons have been computed and added to the diagram. The estimated runoff as given in Bulletin 5, Division of Engineering and Irrigation, California State Department of Public Works, was used to extend the record back to 1870. Lines are drawn on the diagram connecting ends of major changes in trends. Two minor cycles are indicated, one of 22 years with an average annual runoff 19.8 per cent above the base normal and the other one of 30 years with the average annual runoff 10.3 per cent below the base period. The two minor cycles are included within a 52-year cycle having an average 2.4 per cent above the base period. It is desirable, in order to conserve time spent on a study, to use a short period that is consistent with the long-time trend and one in which the data are the most plentiful.

Investigations by the California State Department of Public Works indicate that there is a similarity in the runoff trends of streams in Southern California and the upper San Joaquin River. LYNCH [1931] has made a detail study of past precipitation and runoff in the Los Angeles area that covers a period of some 170 years. In Table 2 are tabulated Lynch's indices of weighted precipitation

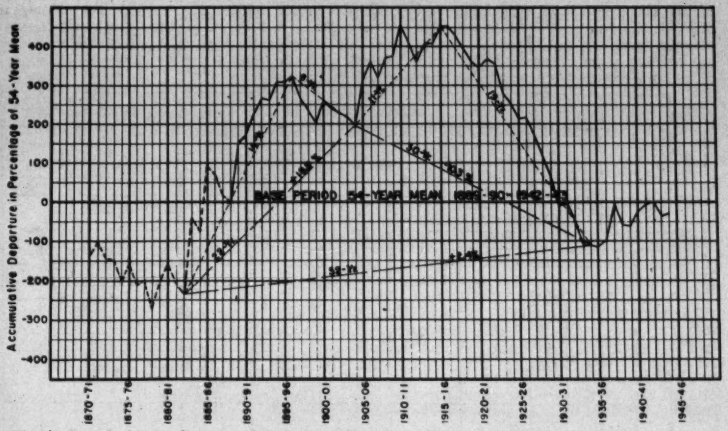

Fig. 1--Residual mass diagram of the natural flow of the San Joaquin River near Friant, California

Table 1--Reconstructed natural runoff of San Joaquin River near Friant, California, from data of California Department of Public Works

Season	Runoff	Season	Runoff	Season	Runoff
	1000 ac ft		1000 ac ft		1000 ac ft
1871-72	2627	1895-96	1986	1920-21	1602
73	1122	97	2220	22	2358
74	1862	98	922	23	1660
75	887	99	1270	24	446
1875-76	2862	00	1344	25	1445
77	809	1900-01	3004	1925-26	1170
78	2218	02	1585	27	2009
79	470	03	1716	28	1168
80	3349	04	1768	29	873
1880-81	2740	05	1526	30	880
82	1000	1905-06	4086	1930-31	489
83	1392	07	2878	32	2062
84	5732	08	1164	33	1116
85	1218	09	2904	34	706
1885-86	5211	10	2042	35	1935
87	1479	1910-11	3588	1935-36	1868
88	957	12	1038	37	2222
89	1574	13	908	38	3705
90	4620	14	2890	39	946
1890-91	2355	15	1965	40	1889
92	2933	1915-16	2777	1940-41	2654
93	2768	17	1952	42	2265
94	1864	18	1472	43	2070
95	2790	19	1303	44	1237
		20	1320	45	2045
54-year (1890-1943) mean natural flow 1,935,000 ac ft					
30-year (1906-1935) mean natural flow 1,740,000 ac ft					

for the Los Angeles are adjusted to the 30-year base period, 1906-1935. A residual mass diagram of these data for the 30-year base period has been plotted in Figure 2 together with residual mass diagrams for the 30-year base period, of the runoff of the San Joaquin River near Friant and precipitation at mountain base stations in the upper San Joaquin River Basin. The 30-year base indices for the mountain precipitation are tabulated in Table 3.

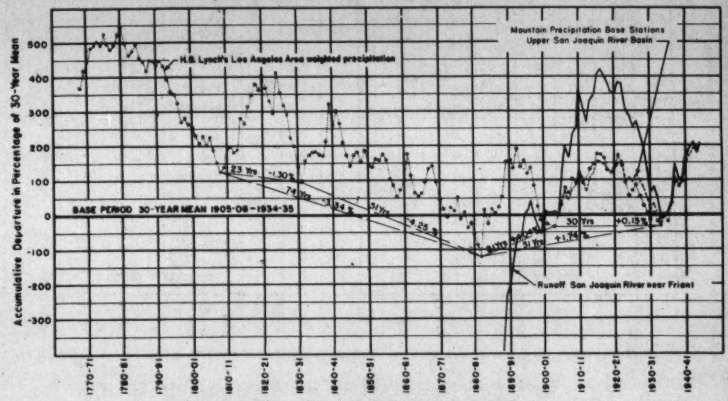

Fig. 2--Residual mass diagrams of weighted precipitation by H. B. Lynch; precipitation at the upper San Joaquin mountain stations, and runoff of the San Joaquin River near Friant, California

The residual mass diagrams of precipitation in Figure 2 show a close correlation both in trend and variation between the precipitation at the mountain base stations in the San Joaquin River Drainage Basin and precipitation in the Los Angeles area. The residual mass diagram of runoff of the San Joaquin River near Friant during the period of record follows the same trend shown by the precipitation, from which it may be inferred that the runoff of the San Joaquin River in the past followed the same trend, with series of years above and below normal, as shown by precipitation in the Los Angeles area. The diagram does not indicate any cycle in the past where the average departed more than a few per cent from the 30-year base period. The runoff record during the 30-year base period contains two critically low runoff years and has a preponderance of subnormal years, which characteristic appears in the precipitation cycles.

Based on the supposition that past trends will recur in the future it may be assumed that the runoff during the 30-year period, 1906-1935, would be representative of the long-time water supply of the San Joaquin River.

Extending short-term runoff records--The mean seasonal runoff for the base period at a required location which has the same coefficient of variation as the base station is determined from the ratio between the summations of the runoff during the period of record at the required location and the runoff at the base station, times the mean seasonal runoff at the base station. The seasonal runoffs for the period of record at the required location are expressed as a percentage of the mean seasonal runoff (designated runoff indices) and are plotted against the corresponding indices of the base station. A smooth curve is drawn through the points, adjusted so that the sum of the indices for the base period at the given location will be equal to the number of years in the base period times 100; the indices for the missing years in the base period being obtained from the curve. For cases where the seasonal runoffs during the period of record are predominantly above or below normal with different coefficients of variation at the two locations it will be necessary to determine the mean seasonal runoff at the required location by trial until the curve fits the above condition; assuming a smaller mean seasonal runoff if the sum of the indices for the base period is less than 100 times the number of years in the base period or a larger mean runoff if the sum of the indices is greater. It is recognized that any seasonal runoff computed from these correlation indices may be greater or smaller than the actual occurrence; however, they will have similar variations and will have the same average for the period. In Figure 3 is shown the correlation curve of seasonal

natural flow indices for the 30-year base period of the 22-year record 1922-1943 of the South Fork of the San Joaquin River near Florence Lake and the San Joaquin River above Big Creek, which latter station was adopted as the base station for the area in which water supply data were required.

Table 2--Precipitation indices of Los Angeles area determined by H. B. Lynch, and adjusted to a 30-year base period, 1906-1935

Season	Index	Season	Index	Season	Index	Season	Index	Season	Index
1769-70	152	1805-06	122	1840-41	39	1875-76	140	1910-11	118
71	122	07	64	42	142	77	37	12	80
72	142	08	73	43	64	78	121	13	79
73	108	09	64	44	44	79	53	14	159
74	112	10	112	45	64	80	115	15	117
75	88								
1775-76	132	1810-11	152	1845-46	68	1880-81	69	1915-16	128
77	73	12	108	47	132	82	67	17	98
78	73	13	83	48	108	83	66	18	90
79	122	14	108	49	73	84	235	19	65
80	132	15	191	50	132	85	60	20	95
1780-81	122	1815-16	83	1850-51	59	1885-86	144	1920-21	101
82	54	17	152	52	93	87	88	22	147
83	64	18	132	53	122	88	115	23	70
84	112	19	132	54	98	89	131	24	52
85	108	20	83	55	117	90	201	25	63
1785-86	73	1820-21	142	1855-56	83	1890-91	106	1925-26	113
87	88	22	64	57	44	92	77	27	116
88	73	23	64	58	83	93	154	28	67
89	132	24	64	59	64	94	48	29	74
90	98	25	215	60	122	95	120	30	80
1790-91	88	1825-26	44	1860-61	88	1895-96	61	1930-31	30
92	112	27	64	62	215	97	116	32	118
93	83	28	72	63	39	98	49	33	76
94	64	29	34	64	49	99	40	34	88
95	64	30	73	65	93	00	62	35	130
1795-96	93	1830-31	54	1865-66	108	1900-01	114	1935-36	82
97	64	32	44	67	132	02	70	37	154
98	54	33	161	68	137	03	134	38	160
99	112	34	117	69	108	04	60	39	87
00	83	35	107	70	54	05	134	40	117
1800-01	93	1835-36	102	1870-71	49	1905-06	131		
02	73	37	93	72	73	07	149		
03	78	38	98	73	78	08	86		
04	122	39	142	74	126	09	137		
05	73	40	205	75	90	10	93		

Monthly runoff quantities are determined in a manner similar to that used for seasonal runoff. Monthly runoffs during the period of record at the given location are expressed as a percentage of the mean seasonal runoff and plotted against the corresponding values at the base station. A smooth curve for each month is drawn through the points, adjusted so that the sum of the monthly percentages for each season will approximately equal the runoff index. A final adjustment is made by changing one or more of the larger monthly values when tabulated so that the sum of these monthly percentages will equal the seasonal index.

In the upper San Joaquin River Drainage Area, approximately 75 to 80 per cent of the seasonal runoff occurs from melting snow during the four months of April-July. In Figures 4 and 5 are shown the monthly runoff correlations for the South Fork of the San Joaquin River near Florence Lake with the San Joaquin River above Big Creek. As might be expected, the monthly values show considerable variation. Nevertheless the sum of the monthly percentages obtained from the curves are within a few per cent of the seasonal index and require only minor adjustments to obtain

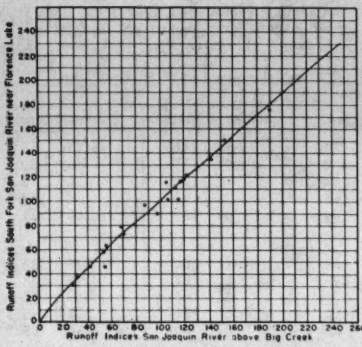

Fig. 3--Correlation of indices of seasonal natural runoff, 30-year base period, 1906-1935

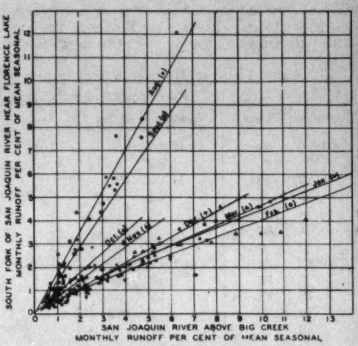
SOUTH FORK OF SAN JOAQUIN RIVER NEAR FLORENCE LAKE MONTHLY RUNOFF PER CENT OF MEAN SEASONAL
SAN JOAQUIN RIVER ABOVE BIG CREEK MONTHLY RUNOFF PER CENT OF MEAN SEASONAL

Fig. 4--Monthly runoff correlation, August-March, 30-year base period, 1906-1935

Table 3--Precipitation indices for mountain base stations in the upper San Joaquin River Basin, 30-year base period, 1906-1935; mean of records for stations at Crane Valley, Big Creek No. 1 Powerhouse, Big Creek No. 2 Powerhouse, and Huntington Lake

Season	Index	Season	Index	Season	Index
1905-06	141	1920-21	100	1935-36	111
07	129	22	119	37	126
08	73	23	109	38	179
09	134	24	43	39	74
10	105	25	110	40	113
1910-11	148	1925-26	88	1940-41	147
12	76	27	118	42	122
13	64	28	89	43	122
14	141	29	77	44	87
15	108	30	71	45	124
1915-16	139	1930-31	62		
17	98	32	121		
18	93	33	72		
19	85	34	69		
20	94	35	124		

Table 4--Comparison between summation of monthly percentages from Figures 4 and 5 and seasonal indices

Season	Season Index	Monthly summation from curves	Variation from curves	Season	Season Index	Monthly summation from curves	Variation from curves
			pct				pct
1905-06	215.3	226.3	+5.1	1913-14	120.7	125.1	+3.6
1906-07	157.3	161.8	+2.9	1914-15	114.8	123.9	+7.9
1907-08	73.3	71.2	-2.9	1915-16	135.7	131.0	-3.5
1908-09	157.9	153.4	-2.8	1916-17	115.3	122.2	+6.0
1909-10	116.3	116.8	0.0	1917-18	92.3	92.7	+0.4
1910-11	200.4	198.5	-1.0	1918-19	78.1	73.2	-6.3
1911-12	67.3	71.1	+5.6	1919-20	83.9	85.2	+1.5
1912-13	60.1	65.5	+9.0	1920-21	94.9	94.5	-0.5

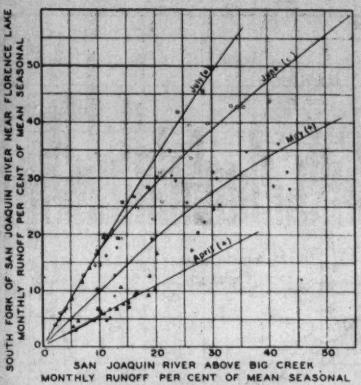

Fig. 5--Monthly runoff correlation, April-July, 30-year base period, 1906-1935

agreement with the season's index. A comparison between the summation of the monthly percentages as obtained from the curves in Figures 4 and 5 and the corresponding seasonal index is shown in Table 4.

Summary--The above described method was used in extending some 15 short-term periods on the upper San Joaquin River to cover the adopted 30-year base period. It was clearly brought out that each subdrainage area has distinctive characteristics which must be recognized in extending the short-term records. The monthly runoffs resulting from melting snow may be delayed or advanced, depending on the elevation and exposure of the area. The deviations from the mean of the seasonal runoffs varies between subareas; one area having higher indices for flows below normal and lower indices for flows above normal. The use of correlation curves provides a method for recognizing these characteristics. With a properly chosen base period the result obtained will be representative of the long-time trend which has been experienced within the drainage area during the past.

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DISCUSSION

Harvey O. Banks (Pasadena, California, February 24, 1948)--The determination of the proper period to be used as a base is the first and fundamentally the most important problem that must be solved in any water-supply study involving precipitation and/or runoff. Not so many years ago, when stream flow and precipitation data were less plentiful than now, engineers were forced to use the entire period of record for such studies. Unfortunately, some engineers still use this technique with results that are frequently quite erroneous.

The basic concepts and techniques described by the author for use in connection with hydroelectric-development studies are equally applicable to other types of water-supply investigations such as ground-water supplies. Care in the selection of the base period is especially necessary in problems involving arid and semi-arid regions where there are great differences between "dry" and "wet" phases of the weather cycle.

Three factors must be considered in the selection of the representative period, namely: (1) Nature, extent, and length of available records of precipitation and runoff; (2) purpose of the water-supply study; and (3) whether precipitation or stream flow is the dominant factor influencing the water supply.

Figure 6, which shows precipitation at City of Santa Paula in the Santa Clara River Valley, Ventura County, California, plotted both in the form of a bar diagram and as a residual mass diagram, will aid the reader in visualizing the relationship of the residual mass diagram to the actual values of precipitation. Consistent records of stream flow in this area did not start until 1927-1928. The diagram indicates that a dry or drought phase in the precipitation cycle started with 1918-1919 and that the succeeding wet phase ended with 1943-1944, a 26-year period.

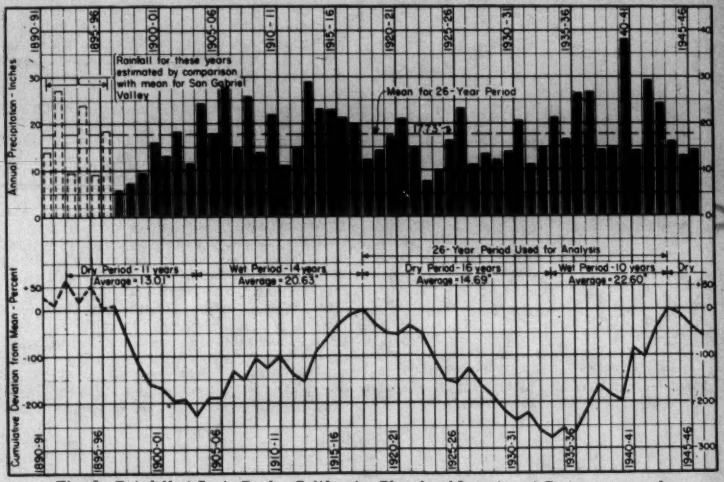

Fig. 6--Rainfall at Santa Paula, California, Blanchard Investment Company record

However, for studies of the underground basins along the Santa Clara River, a 22-year period, 1922-1923 through 1943-1944, can be used since there was more than sufficient runoff in 1921-1922 to recharge the ground-water storage completely, thus somewhat shortening the labor of analysis.

In Southern California a number of precipitation records were started 65 to 85 years ago. We are not so fortunate, however, as regards stream-flow data. Continuous and consistent records of discharge of San Gabriel River started with 1895-1896; of Santa Ana River with 1896-1897; and of San Antonio Creek with 1901-1902. Measurements of a few other streams were started between 1910 and 1920 but wide-spread stream measurement work did not begin until after 1920.

In Figure 7 are presented residual mass diagrams of runoff in San Gabriel River and precipitation on San Gabriel Valley, based on means for the 22-year period, 1922-1923 through 1943-1944. So far as precipitation alone is concerned, the diagram indicates that the 32-year period, 1904-1936, could be used for analysis with some advantage due to greater length. The 53-year period, 1883-1884 through 1935-1936 (not shown on diagram) embracing two wet and two dry phases, would be even better. Stream flow, however, is the major contributor to the ground-water supply of San Gabriel Valley. There are numerous other streams entering the valley besides San Gabriel River but records for most of these do not start until 1916, and after. It is considered, therefore, that more reliable results will be obtained by using the 22-year period even though the diagram indicates that average runoff for the 32-year period was about 12.5 per cent greater. Were the longer period to be used, it would be necessary to estimate a considerable proportion of the runoff into the valley for the first half of the period with attendant possibilities of errors and inaccuracy.

Figure 8 gives residual mass diagrams for runoff in Santa Ana River, precipitation on the mountain area tributary to the river, and precipitation on San Bernardino Valley into which the river flows, based on means for the 32-year period, 1904-1936. Here only the 32-year period can be used at present since no other period is as yet clearly defined by the records of stream runoff.

It cannot be expected that the patterns of precipitation and runoff in the future will be the same as those experienced in the past, on a year-for-year basis. Available evidence indicates, however, that trends tend to repeat. The average result obtained from a study of a representative historical period is as close as it is now possible to come to what may be expected in the future.

It is obvious that the period used should always encompass at least one complete dry phase and one complete wet phase.

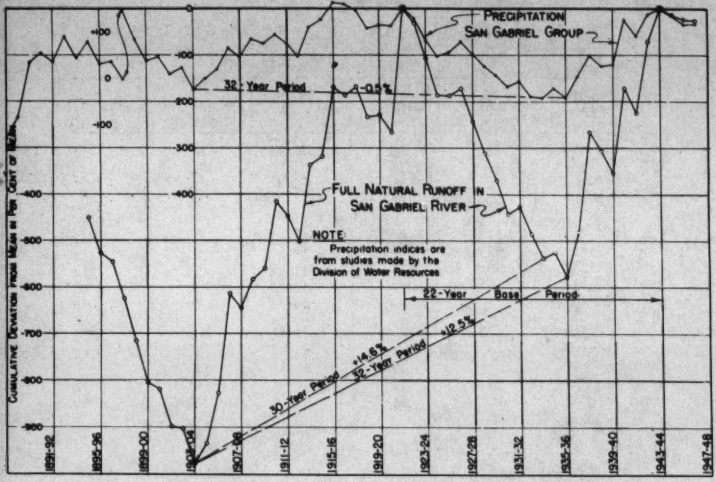

Fig. 7--Residual mass diagrams; runoff of San Gabriel River near Azusa, California and average precipitation of the San Gabriel group of stations, based on 22-year mean

To extend short-term runoff records, the writer prefers the simpler and more direct method of estimating runoff for years of missing record for the short record stream through the use of a

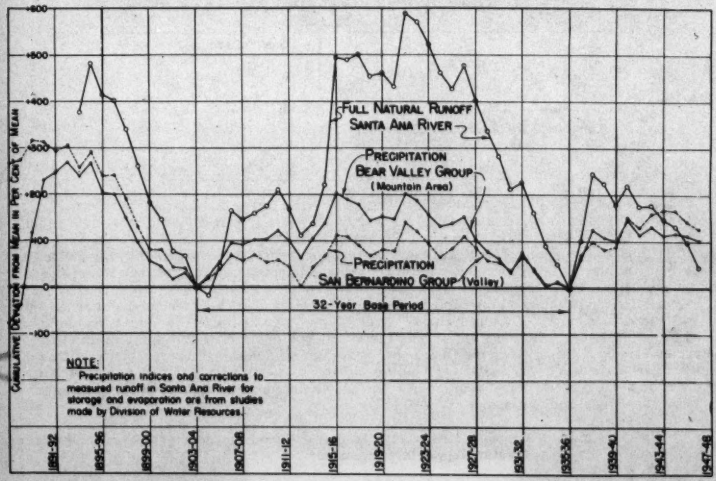

Fig. 8--Residual mass diagrams; runoff of Santa Ana River near Mentone, California, and average precipitation over the Bear Valley and San Bernardino groups based on 32-year mean

curve of relationship with runoff in the long record stream as determined by the period of concurrent record. The mean runoff for the short-record stream is then the average of annual values of measured and estimated runoff for the base period.

Table 5--Comparison of runoff indices[a] for Big Santa Anita Creek and San Gabriel River in Southern California, based upon mean for 22-year period, 1922-1944

Runoff year	Big Santa Anita Creek	San Gabriel River[b]	Runoff year	Big Santa Anita Creek	San Gabriel River[b]
1916-17	86	82	1930-31	21	28
17-18	79	118	31-32	85	115
18-19	19	35	32-33	38	42
19-20	51	105	33-34	53	47
			34-35	95	113
1920-21	54	63	1935-36	62	48
21-22	352	366	36-37	209	195
22-23	52	68	37-38	329	316
23-24	15	25	38-39	57	60
24-25	15	21	39-40	57	52
1925-26	92	99	1940-41	300	283
26-27	110	115	41-42	39	46
27-28	21	29	42-43	353	253
28-29	26	32	43-44	144	172
29-30	27	41	44-45	75	86
			1945-46	66	90
			46-47	..	98
Mean annual runoff, ac ft				4710	111900
Drainage area, sq mi				10.5	211

[a]Yearly runoff expressed in per cent of mean annual runoff for base period.
[b]Values for San Gabriel River are for full natural runoff.

Table 6--Summation of runoff indices for Big Santa Anita Creek and San Gabriel River

Period	Summation of indices	
	Big Santa Anita Creek	San Gabriel River
Dry, 1922-1923 through 1935-1936	712	823
Wet, 1936-1937 through 1943-1944	1488	1377
Sum	2200	2200

Tables 5 and 6 give indices of runoff for Big Santa Anita Creek and for San Gabriel River. The watersheds of these two adjacent streams are widely divergent in size although they are similar geologically and hydrologically, except that the watershed of Big Santa Anita Creek lies on the southerly flank of the mountains. It will be noted that during dry periods, runoff in Big Santa Anita Creek tends to be relatively less, and during wet periods is relatively greater than runoff in the San Gabriel River. This is quite generally true of watersheds of similar geologic and hydrologic characteristics but of different size and exposure. The relationship between values of runoff from the two watersheds cannot be expressed as a straight line. Considerable error may thus be introduced if the mean long-time runoff of a short record stream is estimated from the mean for a long-record stream by multiplying by the ratio between accumulated runoff in the two streams for the period of concurrent record, particularly if the period of concurrent record embraces only years in a wet period or in a dry period. The author's technique can be successfully applied in such cases by using successive approximations.

The author is to be commended for clearly presenting a sound approach to one of the fundamental problems involved in water-supply investigations.

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SOME ASPECTS OF GEOPHYSICS IN CANADA WITH SPECIAL REFERENCE TO STRUCTURAL RESEARCH IN THE CANADIAN SHIELD

(Part 2: An approach to the structure of the Canadian Shield)

J. Tuzo Wilson

Abstract--The use of air photographs in interpreting some geological features of the Canadian Shield is illustrated and the method applied to several large areas. It is shown that many large faults can be distinguished. With the aid of existing field data and physical theory, an attempt is made to classify these structures and to show the direction of the major orogenic forces which produced them. The faults have been divided into groups which it is suggested are connected with the folded roots of several former mountain ranges. The arrangement of these and later ranges outside the Shield suggests that the North American continent has grown by the accretion of successive systems of mountain arranged tangentially along the former margins of the continent.

Introduction

There is at present world-wide interest in the major structures of the Earth's crust. Our understanding of them and of the Earth's tectonic history is being rapidly advanced by supplementing the geological observations accumulated during the past century with data obtained by the use of new methods. In these studies one of the key areas is the Canadian Shield for it forms the core of a symmetrical and isolated continent and its rocks are well exposed over a great area.

In North America itself there are few geological problems whose solution would create wider interest than the elucidation of the structural history of the Canadian Shield. Because of its economic importance most Canadian geologists are working among Precambrian rocks, while in the United States geologists are interested in the Shield because ancient zones of weakness must be expected to exert an influence far across the covered shield of the Interior Plains into the Appalachian and Cordilleran mountain systems.

Those who have attempted to map Precambrian geology know that this unfortunately is difficult and complex. Many years must elapse before the details of the Canadian Shield are interpreted by field methods. The use of new geophysical methods and of air photographs is assisting mapping but there is no indication yet that any combination of these methods will dispense with the need for slow field examination before a full understanding is obtained. On the other hand, there is promise that new methods may make speedy reconnaissance possible and that geophysical techniques will give information about structures that was not available before at depth and under drift and water.

This paper endeavors to show in the first place that information from air photographs can provide useful structural information rapidly over great areas, and in the second place that the information so obtained can be interpreted in the light of physical theory and combined with accumulated field data to give a rough idea of some of the major tectonic features of the Canadian Shield and the forces that must have operated to form them. It is hardly likely that all the conclusions reached in this preliminary effort are correct, but it is believed that the data and ideas are worth recording as they illustrate the use of a powerful new technique to aid geologists in shield areas.

This paper is divided into six sections. Section 1 contains some generalizations upon the progress and limitations of structural field work in the Canadian Shield. Section 2 is a discussion of the use of air photographs in geological work emphasizing the differences between using air photographs as an aid to detailed field work and as an independent method of obtaining reconnaissance information of large areas with little fresh field work. To carry out the latter type of work in the Canadian Shield it is recommended that the pattern of linear topographical features be plotted for an area and that the interpretation be based upon the resulting pattern as much as upon the appearance of the photographs. Illustrations of some of the kinds of patterns and their interpretation are given in Section 3, while Section 4 takes up those believed to be connected with

joints and faults, and gives a theory upon which to base their interpretation. Section 5 applies this theory to several large areas and couples it with existing field data to determine the possible structural history of those areas. Section 6 attempts to link these studies together to arrive at a partial account of the structure of the Canadian Shield.

SECTION 1

Progress and Limitations in Structural Field Geology in the Canadian Shield

Precambrian correlation--It is characteristic of Precambrian rocks that metamorphism, complex structural relations, vast granitic intrusions, migmatization, and lack of fossils make geological mapping of them difficult and uncertain. To these complications are added in the Canadian Shield the further difficulties of great areal extent, inaccessibility, and lack of topographic control which the airplane has reduced but not eliminated. These difficulties and the fact that the incentive for most geological mapping has been economic make it easy to understand why only 11 per cent of the total area of Canada is covered by detailed geological maps. At the present rate several centuries must elapse before the geology of the whole Shield has been studied in detail and elucidated [CHIPMAN and HANSON, 1944].

The concentration of ore in sedimentary and volcanic rocks and in small associated intrusives was early recognized, so that mapping has been concentrated upon the bands of those rocks, whereas the greater areas of intervening granites and gneisses have scarcely been mapped at all. Fortunately, the areas mapped in detail are scattered, so that the geology of the Canadian Shield has, as it were, been widely sampled, although the samples have been selected for economic reasons.

Correlation between the separated remnants of sedimentary and volcanic rocks has been upon the basis of similarities in lithology, upon correspondence in degree of folding and metamorphism, upon the presence of great unconformities, and particularly upon finding similar successions of all of these in different areas [WILSON, M. E., 1939a]. Unfortunately these correlations are uncertain. This is especially so for great distances or when the intervening rocks are covered or are largely granitic. Thus the geological history of the whole Precambrian Shield is still little known even if the succession in some small areas is agreed upon.

Structure in the Precambrian--In most parts of the Shield outcrops occur as a succession of glaciated knobs of rock protruding from larger areas of soil and muskeg. Naturally these knobs are the most resistant features so that faults are seldom seen, but hard, indurated rocks, metamorphosed by igneous activity, folding, and time are well exposed. It was thus natural that petrological aspects were emphasized by the early workers at the expense of structure.

Only in a few parts of the Canadian Shield and notably in the vicinity of Yellowknife, N. W. T., are drift, soil, and vegetation very sparse so that excellent exposures plainly reveal many faults as is shown in Figures 1 and 2 [see also JOLLIFFE, 1942a, 1945]. In these places, and from underground geology in mines, there has come a realization of the importance of faults in determining the location of ore and the discovery that many drift-covered valleys hide beneath then the trace of important faults which, being rarely visible, were infrequently mapped by the early geologists; for example, compare COLEMAN [1905] and INTERNATIONAL NICKEL COMPANY [1946] or TODD [1928] and THOMPSON [1945].

It was possible in preliminary surveys to omit faults whose offsets would have been clear in younger or less altered and contorted rocks because of the peculiar complexity of Precambrian rocks and the large areas of drift, but modern detailed maps of small areas [for example, see THOMPSON, 1945; WILSON, M. E., 1939b; or JOLLIFFE, 1942b] reveal complex patterns of faulting which may be suspected to extend to all parts of the Shield. A major effort is now being made by the Canadian Institute of Mining and Metallurgy to collect the structural data available in all Canadian mining areas and publish them as a symposium edited by M. E. WILSON [1948].

Air photographs and geophysical methods often show discontinuities like faults better than they show differences in lithology. Frequently they are also quickly obtainable. There is thus promise that these new methods may be strongest where past field work has been weak and that the combination of new methods and existing field data may together lead to a rapid understanding of the structure and history of the Canadian Shield. This paper indicates the part that air photographs may play in that advance.

Fig. 1--Straight transcurrent (strike-slip) fault with three-quarter mile displacement cutting Archean volcanic rocks (dark and rough) and sedimentary rocks (light and bedded) on the shore of Indin Lake, N. W. T. (R. C. A. F. photographs A8740-119 and 121)

Fig. 2--Looking south along a curved contact between granite (to east) and folded Proterozoic Snare group; this contact may be a thrust fault dipping steeply west; it has been called the Snare Lineament (R. C. A. F. photograph A4733-86L)

SECTION 2

Ways of Using Photographs and Topographic Maps in Mapping Structure

It will be well to distinguish immediately between two different ways of obtaining geological information from air photographs. The usual method depends upon identifying features by their appearance on each photograph. Another method, which will be emphasized in this paper, does not

demand that features be identified on the photographs but only that enough be seen to enable a pattern to be plotted on a map. In many cases the pattern resulting from the study of many photographs has characteristics that enable it to be interpreted even though the features are displayed too poorly to be identified directly on any of the pictures. The first method is much the better where it can be applied but the second is the only one possible in the majority of areas [compare Figures 18 and 31].

Fig. 3--Standard R. C. A. F. oblique survey photograph; linears can be seen in the foreground and along rivers in the distance; Christiansen Rapid, which is marked with a circle is also shown in the next two photographs; the foreground is two miles across; that part of the large lake visible is 13 miles long (R. C. A. F. photograph A5008-584)

Fig. 4--Low oblique of area enclosed in circle in Figure 3; no linears can be seen and the forest appears thicker (R. C. A. F. photograph A2566-73)

Plotting from photographs--Most of the many articles on geological use of air photographs and nearly all of the magnificient air photographs published in them deal with visible and recognizable structures [GEOLOGICAL SURVEY OF CANADA, 1947b]. It is therefore disappointing when one examines the air photographs of most areas in northern Canada to find a monotonous pattern of forest or tundra which effectively conceals the rocks in all but a few places. One method of overcoming this is to have photographs specially taken before the leaves are out in the spring, preferably on a large scale. These show outcrops well and are recommended for detailed mapping, but some other approach is needed to make use of the approximately two million survey air photographs already on file in the National Air Photograph Library in Ottawa and other similar pictures.

To illustrate what may be done with uninviting material, consider a parallel from field geology. In exceptional cases a whole folded structure or intrusive mass may be visible on an exposed cliff or bare mountain side. Such cases are used as text-book illustrations without disguising the fact that most structures have to be delineated by making some suitable field observation such as strike and dip on scattered outcrops and plotting many of these on a map before the hidden structure is revealed. To use air photographs in the same way it is only necessary to select some suitable minor type of marking which can be read from the least promising photographs, plot sufficient of these and see if a wider interpretation can be made of the plotted pattern.

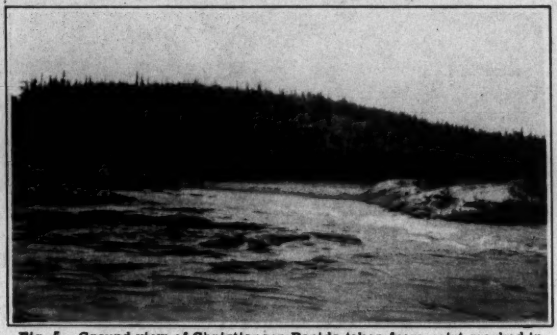


Fig. 5--Ground view of Christiansen Rapids taken from point marked in Figure 4; the forest appears dense and nothing can be seen of structural linears (photograph by author)

Linears--On the basis of experience the features suggested as suitable are straight or gently curving valleys or scarps. Nearly every photograph of the Shield area shows such linear topographical features henceforth to be called "linears." The term will be confined in this paper to features of any origin conspicuous enough to be seen in air photographs of the types commonly used for survey purposes. The word "lineament," which has sometimes been used in the same sense, is here used for a large zone of many parallel or nearly parallel linears or faults [RANSOME, 1915]. Their existence is seldom hidden by the mantle of forest or drift though the cause of them may be so hidden. After enough have been plotted, the pattern has frequently been found to suggest their common cause, be it glaciation, faulting, or foliation. The interpretation of patterns of linears is discussed in the next section.

Scale--The matter of scale is another aspect of the use of air photographs which deserves mention. In this respect there is much the same relationship between the study of air photographs and field work as there is between field work and microscope examination. Given enough microscope slides and their locations, an excellent map of the lithology of an area could be made, but it would be difficult to map structure in this manner. On a larger scale the geologist working in the northern woods has a limited view of structure. He may know when he is in a valley but not easily be able to tell whether it is long or short, straight or irregular, and whether there are others parallel with it or not.

One muskeg, or lake, or patch of drift looks much like another on the ground. If the margins are of different metamorphic rocks, it is difficult to tell whether this is due to igneous activity, folding or faulting. The air view gives one a grander view and those valleys that are straight

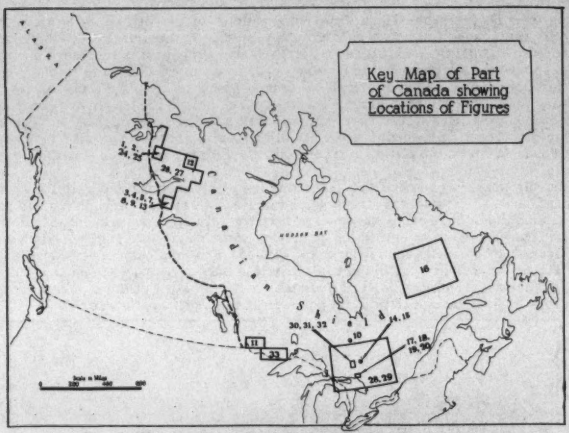


Fig. 6--Key map showing location of other figures, which are indicated by numbers

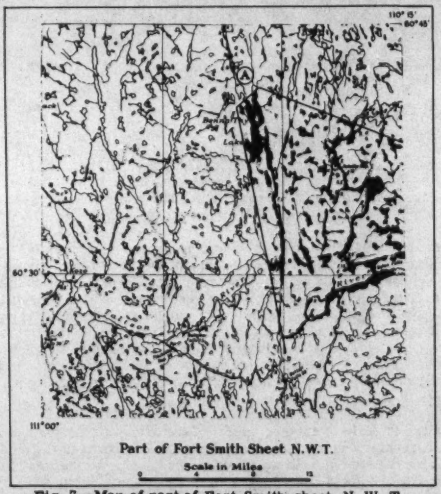


Fig. 7--Map of part of Fort Smith sheet, N. W. T., showing numerous lakes typical of much of Canadian Shield; some are arranged in continuous lines, or linears; the position of Figure 8 is indicated by the inking of the lakes

and narrow for long distances stand out from the rest and suggest the presence beneath them of faults, although the photographs may tell nothing of the kinds of rock on either side. Many of the existing reconnaissance maps show lithology only, so that in combination these two methods supplement each other.

The limitations of the ground view are plainly seen in the succession of photographs taken at different altitudes and reproduced as Figures 3, 4, and 5. Figure 6 is a key map showing the locations of the figures of this paper.

Use of topographic maps--For a preliminary survey of the linear pattern, it is possible to use good topographic maps because drainage usually follows linears, but it is much better to examine the photographs. Maps may be used by emphasizing straight and gently curved lines of drainage directly on them with a colored pencil. These are linears.

Figure 7 shows part of a map originally published on a scale of four miles to one inch. The location of the R. C. A. F. oblique survey photograph reproduced in Figure 8 is indicated on it. Figure 9 shows the linears drawn for the same area by examining these and other similar photographs. This area has been discussed elsewhere [WILSON, J. T., 1941b]. The prominent north-south group of curved linears which is equally clear on either photographs or map has been called the Taltson Lineament and is believed to be a zone of thrust faults. The term linear [HOBBS, 1904] has been reserved for the topographical expression shown by individual valleys or scarps while lineament [RANSOME, 1915] is a broader term meaning a complex zone of linears or faults.

Fig. 8--Photograph of the shaded part of Figure 7; the arrangement of chains of lakes along linears is more strikingly shown on the photographs; the chief linears are probably thrusts and are part of the Taltson lineament (R. C. A. F. photograph A5008-39R)

Peculiarity of the Shield--It may be asked why it is, if the pattern of linear topographic features provides assistance in determining structure, that the method has not come into more widespread use, but it must be emphasized that two special conditions apply in the Canadian Shield that make the method more effective there than it would be in most other parts of the world. It is agreed that in most other regions the drainage pattern may not reflect the structure closely.

In the first place, most Precambrian rocks are indurated and thus stand up well to erosion in contrast to the gouge, carbonate rock, and schist often found along faults. This contrast is not so marked in rocks outside the Shield where soft beds of shale or unconsolidated material may be eroded in preference to faults. The second feature is that according to COOKE [1931], the Shield was reduced to a fairly perfect peneplain by Pliocene time. The peneplain was then uplifted several hundred feet and eroded to a state of late youth before glaciation occurred. This rejuvenation of a level plain provided an opportunity for erosion to select the soft fault lines for deepening into valleys. Pleistocene glaciation led to many of these valleys becoming first further eroded and later choked by glacial deposits so that they have become chains of elongated lakes and muskegs which now show plainly on air photographs and on topographic maps.

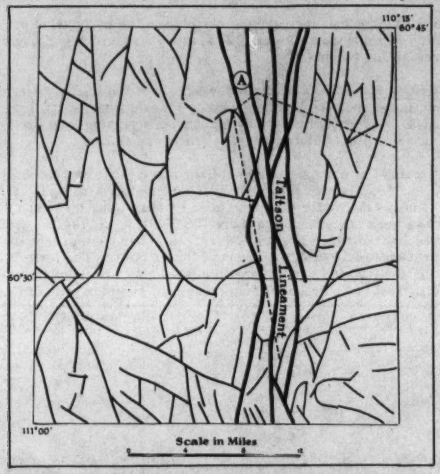


Fig. 9--Map of same area as Figure 7, showing pattern of linears derived from study of similar air photographs to that shown in Figure 8

Fig. 10--Photograph of part of the northern Ontario clay-belt which was overridden by a late readvance of the Wisconsin ice sheet; the direction of glaciation shows plainly and controls the distribution of lakes, muskeg, and forest; the sides of the photograph are 2 1/4 mi long (Ontario Dept. of Lands and Forests photograph 47-5-276-53)

SECTION 3

Patterns of Linears and Their Interpretation

Outcrop or drift--In areas of predominantly bare rock, such as those around Yellowknife discussed by Jolliffe, the bedrock pattern is distinct. The linears are chiefly due to faults and joints, but often, rock types, foliation, and bedding can also be seen (see Figs. 1 and 18). On bare rock the direction of glaciation can seldom, in the writer's experience, be determined from air

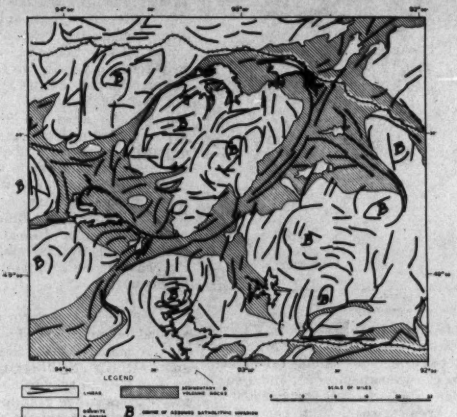


Fig. 11--Sketch map of area immediately west of Lake of the Woods and north of Rainy Lake, showing centers of assumed batholiths (B) as deduced from linears drawn from topographic maps with the scale of 8 mi/in; the areas of granite and sedimentary rocks which were added later suggest that this interpretation was correct

photographs. On the other hand, in areas of sand plain or heavy muskeg, nothing can be seen of the bedrock, and the glacial drifts control the patterns (see Fig. 10). Most areas fall between these two extremes, and a mantle of drift, some of whose features can be interpreted, alternates with and partly obscures bedrock, something of whose pattern also shows through even when diagnostic characteristics are hidden (see Fig. 8). The pattern of linears formed by one type of glacial deposit and five types of bedrock features have been recognized by the writer, and are described below.

Direction of glaciation--The direction of glaciation is usually consistent over small areas as Figure 10 illustrates or else it shows as a series of broad fan-shaped patterns a hundred or so miles across corresponding to ice lobes. Since the approximate direction is usually known from previous mapping or the recognition of specific drumlinoid features, it is not hard to see what part of a linear pattern is due to this cause and what other patterns can only be due to bedrock. The writer has not encountered any areas where two or more intersecting or superimposed sets of features due to glacial movements can be seen in photographs. The direction of drumlinoid features is on the contrary much more consistent than are striae, and most intersecting striae are suspected to be due to eddying under a single ice sheet. This way of identifying and mapping direction of glaciation can be quickly used in most parts of the Shield.

Many other glacial and post-glacial features can be occasionally recognized in photographs, but they have not been found to produce extensive patterns of linears. When the direction of glaciation has been eliminated, the remaining pattern must be due to bedrock. The use of air photographs to map drift features in northern Canada has been discussed by others, such as NICHOLLS [1932], NORMAN [1938], SPROULE [1939], SATTERLY [1940], WILSON, J. T., [1939], and WASHBURN [1947].

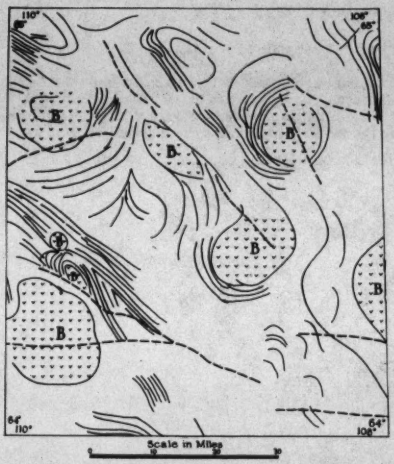


Fig. 12--Linears of Aylmer Lake area, N. W. T.; little of the geology of this area is known, but the linears shown are predicted to be due possibly to bedding in sedimentary rocks where numerous, and elsewhere to foliation in gneisses; it is suggested that the checked areas are batholithic centers while the dashed lines may be faults

Patterns due to batholithic instrusives--In several parts of the Shield, roughly circular patterns of several concentric parallel rings stand out plainly. These resemble the classic examples of foliation mapped by ADAMS and BARLOW [1910].

Figure 11 illustrates the pattern obtained in the Rainy Lake region by emphasizing rivers, creeks, and regularly curved lake shores. It reveals a pattern which after comparison with the known geology can only be interpreted as due to foliated batholiths. Other examples can be seen in the Fort Smith sheet [WILSON, J. T., 1941a] and Ingray Lake sheet (see Figs. 24 and 25) and are common in Grenville rocks. This type of pattern is so plain in an unmapped area northeast of Yellowknife that a prediction is made in Figure 12 of what type of geology may be expected in the region when it comes to be examined in the field. The figure is based upon a plot of linears made by a colleague, G. H. Charlewood, from oblique air photographs with interpretation added by the writer.

Foliation is sometimes only conspicuous around the periphery of a batholith, which may be massive towards the center. ADAMS and BARLOW [1910] recognized this in the case of the Cheddar batholith which they mapped. Massive granite is jointed with a cross hatched instead of a concentric pattern. In areas of thin drift the joints may be marked by a rectilinear tracery of small L-shaped lakes, which may often be recognized. Foliated and bedded rocks show elongated but not L-shaped lakes.

Fig. 13--Photograph from Fort Smith area, showing five parallel valleys; field examination showed that the creek in the central valley is along a dike; it was suspected that the other valleys might also follow dikes and this was proven in places (R. C. A. F. photograph A5120-5C)

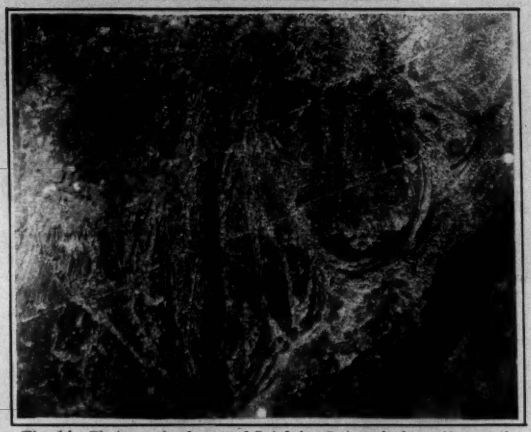


Fig. 14--Photograph of area of flat-lying Gowganda formation south of Larder Lake; it is suspected that the fine straight lines of light color are due to diabase dikes; photograph 1 3/4 × 1 1/4 mi (Ont. Dept. of Lands and Forests; photograph (46-91-210-125)

Fig. 15--Outcrops of flat-lying Gowganda quartzite and conglomerate south of Larder Lake, showing bedding; area is 1 3/4 × 2 1/2 mi (Ontario Dept. of Lands and Forests, photographs 1/46-94A-304-69 and 70)

Patterns due to diabase dikes--Many of these are so narrow that they cannot be distinguished upon small-scale vertical or oblique pictures unless very conspicuous. Sometimes they show as rock ridges or as narrow dark or light bands across outcrops. One diagnostic feature more noticeable from the air than on the ground is cross jointing, giving a ladder-like appearance. This is due to cooling fractures and has long been recognized in sills where it may be even better developed (as at Giant's Causeway, Ireland).

Dikes follow tension cracks, normal faults, and occasionally transcurrent faults. They frequently occur in swarms and where short sections have already been mapped on the ground, connections and extensions can be predicted along linears from photographs (see Figs. 13 and 19). In forested country linear patterns marked by change of foliage can be suspected to be due to dikes (see Fig. 14). Dikes commonly are straight or nearly so.

Patterns due to bedding--Without outcrops or field information this pattern may be difficult to recognize, but is quantitatively unimportant. Adjoining linears must obviously be parallel. Bedding is usually curved either because the beds are folded or because erosion has made curved outcrops in flat beds (see Fig. 15). Where beds dip steeply the hook shapes due to folds may show up well even on topographic maps (see Fig. 16). Beds vary in hardness and the same softer ones tend to be eroded away in different parts of the pattern.

Patterns due to foliation--The foliation of gneissic rocks has much the same characteristics as does bedding, indeed in many cases it is the metamorphic equivalent. It shows up especially well in Grenville gneisses. Since gneissic rocks supply little overburden, foliation is often well exposed in them. A splendid illustration may be taken from the Delamere Sheet, mapped on one inch to one mile in three field seasons by QUIRK and PEGRUM [1930].

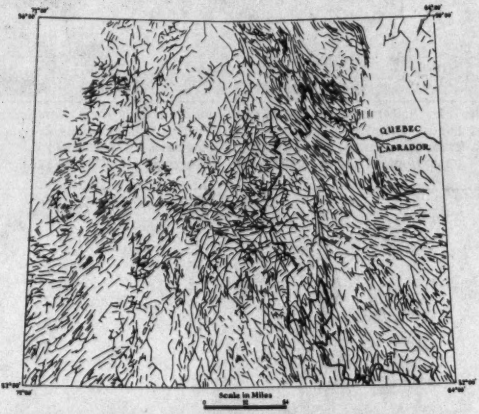


Fig. 16--Sketch map of central Ungava showing linears drawn by emphasizing drainage on eight-mi-to-one-inch topographic maps (Nichicun, Kaniapiskau, Ashuanipi, and Dyke Lake sheets); folded iron formation striking NW-SE occupies the NE corner; the rest is believed to be granite gneiss with NE-SW faulting

The area shown in Figures 17 and 20 is that covered by the Delamere and the northern part of the Key Harbour sheets [QUIRKE, 1929, 1930]. The region is underlain by contorted ortho- and paragneisses, granites, and remnants of metamorphosed sedimentary rocks. After being glaciated, the area was covered by post-glacial Lake Algonquin, whose waters, as they fell, washed the higher ground bare and deposited the drift as varved clays and as silt in the hollows. As a result, the foliation is well exposed and it was mapped from vertical photographs (scale, 1320 ft to one inch) with a stereoscope (see Fig. 17). Crossing the foliation are later faults and tension cracks shown on the map as linears. These may be of more than one age and several of the later ones are known to be occupied by diabase dikes. It is suspected others are also. The foliation agrees very closely with the geological boundaries mapped by Quirke in the field, which have been generalized in Figure 20, but Quirke's map did not indicate the synclines and anticlines, nor did he give any structure section. One day's field work by the author determined the plunge of two synclines and enabled the synclinal and anticlinal axes and the structure section based upon the combined work to be drawn. Figure 18 shows one of the photographs of the main syncline. It is asymmetrical and in order to match the two sides, it is necessary to assume that the continuous linear seen one

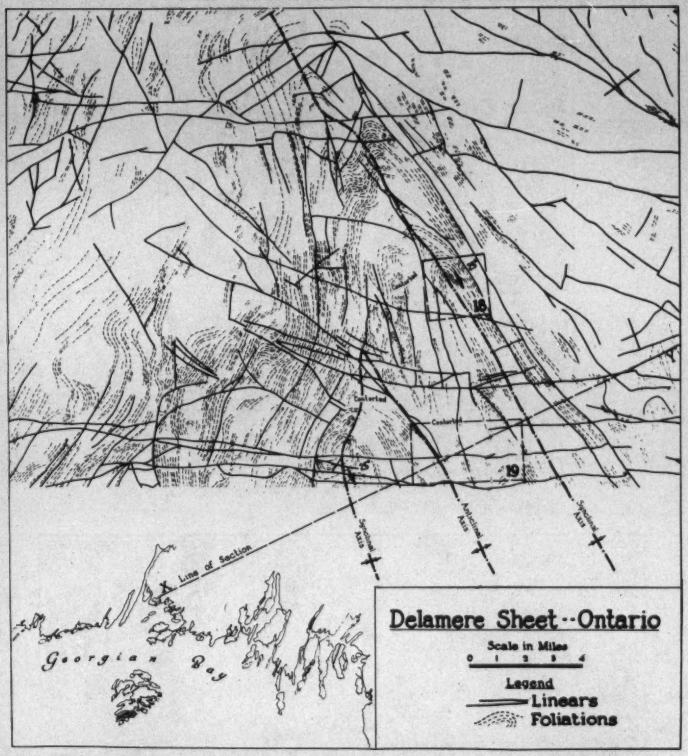


Fig. 17--Linears and foliation drawn from vertical air photographs for Delamere sheet, Ontario; the location of Figures 18 and 19 is shown; the only information not secured from the photographs is the plunge of the synclines

mile east of the main syncline is a major fault. This is the more likely since the linear continues for 20 miles north of this area until it meets the Huron-Mistassini thrust. This interpretation brings out the fact that several of the syenite and diorite masses mapped by Quirke form an inverted W-shape and are conformable with the folding. It was suspected that they might be phacoliths until the field was visited, when it was discovered that they are highly gneissic, so that it is believed that they are either altered and recrystallized lava flows or extremely altered sediments. The old bedding is, in fact, marked by the foliation.

Figure 19 shows the French River crossing foliated gneisses. It was found that the outcrops of diabase mapped by Quirke along its channel are all only remnants adhering to the granite shores, which strongly suggests that large dikes occupy the bed of the river. The shape of the shores shows that there can have been no horizontal movement along this linear and it is suspected that it is a tension crack of very late Precambrian age.

Thus it is believed that a brief examination of the air photographs has added materially to knowledge of the district. Quirke himself realized that they would have been of great assistance,

Fig. 18--Synclinal fold plunging 25° south with steeply dipping limbs of pink and grey, garnetiferous biotite paragneisses; Rutter Station is at the road junction; area is 2 1/4 mi square (Ontario Dept. of Lands and Forests; photograph 46-172-173-200-24)

Fig. 19--Foliated paragneisses with a drag fold in the upper right corner; the French River crosses the area, which is 2 1/4 × 4 mi; the pattern of parallel shores suggests that the valley is a tension crack, while remnants of diabase suggests that the bed is along a diabase dike (Ontario Dept. of Lands and Forests, photograph 46-176-6-58 and 59)

for after his field work had been done without them, he was able to obtain a few early oblique air photographs, and points out their value [QUIRKE, 1929].

SECTION 4

Patterns Due to Faulting and Jointing and a Theory to Aid in Their Interpretation

It has been found that the linears due to the previously discussed causes are minor quantitatively and can usually be recognized, leaving the great bulk of linears due to joints and faults. The several classes of these may sometimes be distinguished in the linear pattern. As an aid in making distinctions, the theory of faulting will now be reviewed so that it can be used to predict the habits of linears due to different classes of faults.

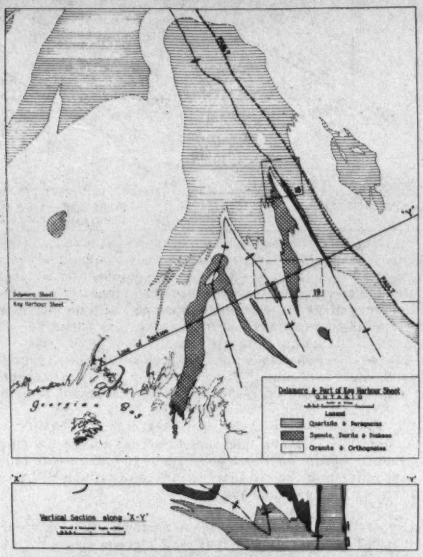


Fig. 20--Geological sketch map of the same area as Figure 17, showing location of Figures 18 and 19; the formation boundaries have been taken from the Delamere and Key Harbour sheets; comparison with the other figures shows how much additional structural information can be added by examining the air photographs

Theory of faulting--ANDERSON [1942] has given a lucid account of physical reasons for the three types of faulting and illustrated this with examples from Great Britain. The aid of this useful exposition is gratefully acknowledged and the next few paragraphs are largely drawn from Chapter II of that book.

Any stresses acting at a point may be replaced by three equivalent but mutually perpendicular principal stresses (see Fig. 21a). At each point there are therefore three mutually orthogonal planes that include two axes of principal stress each. These are the planes across which only normal stresses act (that is, pressures or tensions), and across which no tangential forces act (that is, they are planes of no shear). The surface of the ground is obviously a plane of no shear, since the shearing effects of wind and water are negligible. Thus at any point, which was near the ground surface at the time the forces acted, the stress ellipsoid could only have been oriented with one of these three planes parallel with the ground surface and hence with either the major, intermediate or minor axis of stress approximately vertical (Fig. 21b illustrates the third case).

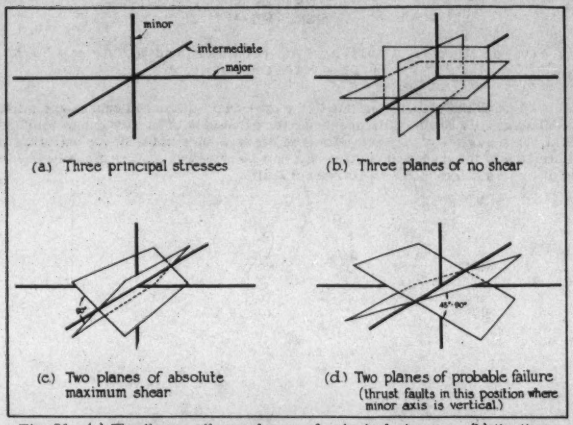


Fig. 21--(a) The three orthogonal axes of principal stresses; (b) the three planes across which there is no shear because each plane includes two of the axes; (c) the planes of maximum shear bisecting the angles between the major and minor axes; (d) the two planes of probable fault failure; they make smaller angles than 45° with the major axis since failure depends upon normal as well as shear pressure

At each point there are also two planes across which no normal stresses act and across which tangential stress is an absolute maximum. These planes of maximum tangential stress bisect the right angles between major and minor axes and include the intermediate axis (see Fig. 21c).

When shear failure occurs in rocks, it does not exactly follow these 45° planes of maximum tangential stress because failure depends upon normal stress across the plane of failure as well as upon tangential stress. Pressure across a plane tends to make shear failure along it less likely and in these circumstances it can be shown that the planes of failure will make a smaller angle with the major axis of stress than 45° (see Fig. 21d).

In 1833 Navier suggested that this effect of the normal stress upon shear failure is a constant for any material. Although this is not precisely true, Anderson shows that it is a satisfactory approximation and that in rocks shear failures, that is, faults, make angles of about 25° rather than 45° with the direction of maximum pressure.

The uniform strike of mountains shows that orogenic forces are fairly uniform over great distances so that these considerations apply not only to points but often also to large areas. To some extent the same ideas apply to depths also, but we shall see that there may be exceptions where erosion has been very deep.

Anderson points out that the three classes of faulting, that is, thrust, transcurrent (or strike-slip), and normal, correspond to the three cases where the minor, intermediate, and major axes respectively are vertical, and that in each case the faults lie along the predicted planes of shear failure. Any of the faults may be found in conjugate pairs parallel with the pair of planes of failure. He also points out that the fault surfaces are straight along their directions of movement but may be curved or corrugated across that direction (slickensides are miniature examples of this effect). Anderson concludes that the properties of the three classes of faults found in Paleozoic deformations in Great Britain fit this physical interpretation. This is certainly true in a general way except that in any one area only one set of a conjugate pair of fault directions is usually developed. This is no doubt due to the effects of anisotropy, and only that set develops which can follow most closely preexisting planes of weakness.

The recognition of faults and directions of orogenic forces from linears--Anderson's conclusions are summarized in Table 1, while Figure 22 illustrates for fault traces the directions and shapes which can be expected from a single orogenic pressure. This suggests a means of identifying the nature of major faults and the directions of the pressures that caused them by an examination of linears. For thrusts should be curved (see Fig. 2 and 8) and approximately normal to the pressures that formed them, while transcurrent faults should be striaght (see Figs. 1 and 31) and make angles of about 25° to 30° with the maximum pressure axes. On which side of a transcurrent fault the pressure axis lies can be told if the direction of movement of the fault is known or from splay faulting [ANDERSON, 1942, p. 150]. Normal faults should not be formed as primary features during an orogeny because mountain building implies great horizontal forces; whereas normal faulting can only occur when all horizontal forces are less than that due to gravity (that is, when major principal axis of stress is vertical).

Table 1--Classes and characteristics of faults as predicted by the theory of Navier and Anderson

Property	Normal	Transcurrent	Thrust
Nature of outcrop of structure	Curved	Straight	Much curved
Nature of dip	About 65° and uniform	About 90° and variable	About 25° and uniform
Direction of movement	Down dip	Horizontal	Up dip
Principal stress which is vertical	Major stress	Intermediate stress	Minor stress
Connection with orogenic forces	None for greatest stress is vertical (equals gravity)	Make angles of about 25° with mountain building forces	Approximately normal to mountain building forces
Nature of fracture	Brecciated	Brecciated or sheared	Sheared
Intrusives along fault plane	Dykes common	Dykes possible	Intrusives unlikely

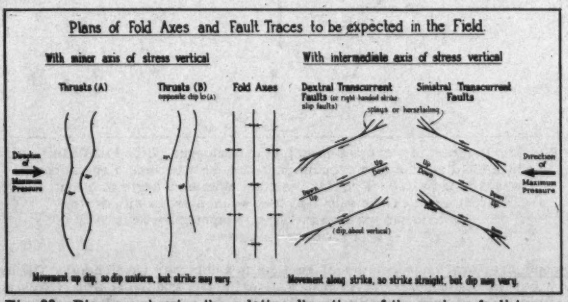

Plans of Fold Axes and Fault Traces to be expected in the Field.
With minor axis of stress vertical
With intermediate axis of stress vertical
Thrusts (A)
Thrusts (B)
opposite dip to (a)
Fold Axes
Dextral Transcurrent Faults (or right handed strike slip faults)
Sinistral Transcurrent Faults
(plough or horsetail area)
Direction of Maximum Pressure
Movement up dip, no dip uniform, but strike may vary
Movement along strike, no strike straight, but dip may vary.

Fig. 22--Diagram showing the relative directions of the various fault traces and fold axes that may be expected as a result of any single period of orogeny

Complications may be due to the superposition upon the pattern produced by one orogeny of patterns of normal faults or of other later orogenies differently oriented, or due to inhomogeneities or secondary faults, but theory and experience suggest that these difficulties can often be overcome if some geology is known in the area under consideration. For example, normal faults

should not be so extensive as the other classes. They are often associated with diabase dikes and should have gently curved patterns. The faults of later orogenies make much more distinct linears than do the faults of an earlier one. Old faults that have not been reopened have no doubt become sealed and are less likely to be eroded rapidly. Secondary faults may be missed if only the largest features are studied. The effect of diverse rock types does not seem to be great. This last suggests that Navier's hypothesis that the angle of failure depends upon the material is not so correct as would be a theory connecting the angle of failure primarily with the relation existing between the three principal stresses and secondarily with the material. (I am indebted to a mathematician, H. O. Seigel, for this suggestion which he is now investigating as part of a mathematical study of types of failure.)

Anderson's theory has been found sufficient to explain many features of linears but it does not explain one type of fault often postulated in the Precambrian. That is the high angle thrust fault, but it too can be explained without disturbing this theory of faulting if the axes of the stress ellipsoid became tilted. This can happen, as Anderson points out, in mountainous country where the mean ground altitude may be far from horizontal; and it may also probably happen at depth in tectogenes where downward forces act to form the roots of mountains. The fact that thrusts in young elevated ranges usually dip gently indicates that the stress axes are not significantly tilted near the surface. On the other hand, at depth the weight of overlying rocks may be sufficient to give a downward component to the major orogenic forces which pushes the roots of mountains down to form tectogenes and in so doing tilts the stress axes. If so, steep thrusting would only be found in the roots of deeply eroded mountain ranges and would flatten out near the surface as HESS [1938] and others have postulated (see Fig. 23). Only in old thrusts, where there has been deep erosion, would the steeper part be visible; those of younger origin even in Precambrian rocks would appear to be gently dipping like the Middle Paleozoic thrusts in the Precambrian of the Scottish Highlands.

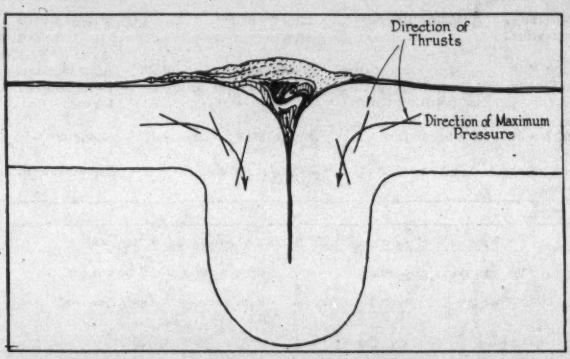


Fig. 23--Diagram of a crustal down fold or tectogene (after Hess); the way in which the direction of maximum pressure must become directed downwards is indicated; if thrusts maintain a uniform angle with that direction, it can be seen that they would steepen with depth; erosion has exposed the steeply dipping portions of Precambrian thrusts

Linears and structural interpretation of Fort Smith and Ingray Lake sheets--The area lying between and about the eastern parts of Athabasca, Great Slave, and Great Bear Lakes is only covered by thin patches of drift so that good exposures make this an excellent region in which to study Precambrian geology. STOCKWELL [1936a and 1936b] and HENDERSON [1939] had both shown the existence of large faults south of Great Slave Lake before 1938 in which year the writer mapped the Fort Smith area dimly realizing that many conspicuous and straight or gently curving valleys (see Figs. 7 to 9) formed a regular pattern that had structural significance, but this was not well checked because the area is almost entirely underlain by a complex of granites and gneisses and because more than 5000 sq mi were reconnoitered by a small party in one summer. However, both a geological map [WILSON, J. T., 1941a] and a study of the linears [WILSON, J. T., 1941b] were published and it was suggested that many of the linears (then called lineaments) were faults and that some of these faults were very large indeed.

Meanwhile JOLLIFFE [1937, 1942a, 1942b, and 1945] and HENDERSON and JOLLIFFE [1939] had showed that many faults near Yellowknife coincided with linears while many other examples have been found elsewhere in the Shield [for example, HOBBS, 1911; COLLINS, 1917, pp. 16-17; BRUCE, 1940, pp. 1-50; MOORE, 1931, pp. 16-17; and NORMAN, 1947, pp. 9-11]. The connection between faults and many linears being thus clear, the author, when assigned to the Ingray Lake area in 1939, plotted from air photographs similar to those shown in Figures 1 and 2, a map of linears before entering the field (see Fig. 24). It was not interpreted at the time but it was found to assist greatly in the geological mapping of the south half of that little-known area and confirmed

Fig. 24--Map of linears of Ingray Lake area, N. W. T., plotted from air photographs before any geology had been done in the area; the letters may be used to compare this figure with the next

the view that linears do indicate much geology and particularly faults. A simplified sketch of the geology is given in Figure 25 [for full detail see LORD and WILSON, 1942]. In the southeastern part a series of strong parallel linears (DD on Figures 24 and 25) striking northwest across Indin (formerly called Wray) Lake were found to be large faults with sinistral horizontal movement totalling more than six mi. These linears are so long and conspicuous that they are used by pilots as flight paths all the way from Yellowknife 135 mi to the southeast. There is little doubt that the faults mapped at Indin Lake follow the linears and are the same faults as those mapped at Yellowknife [JOLLIFFE, 1942b] where they have a sinistral horizontal movement of about 11 mi. This being so, the zone is important, and will be called the Indin Lineament as shown in Figures 26 and 27. The zone of linears EE was shown in the field to be dextral transcurrent faults. The linear AA is considered to be a thrust while BB and CC were shown to be other faults. The many parallel linears FF are due to bedding while Y and the Z's are patterns due to massive granite and foliated batholiths, respectively.

Lest it still be thought that this idea of linears is a fallacy and that the author's mapping was influenced by theories, it should be pointed out that C. S. Lord mapped the north half of the Ingray Lake area the following summer. Due to the disturbance caused by the start of War, he mapped it without any reference to the author's work or without even knowing that a map of linears existed. Nevertheless his independent geological mapping and subsequent detailed work by STANTON [1947] fit the patterns of linears just as well as the writer's mapping. The existence of linears and their frequent coincidence with faults is widely recognized and used by prospectors. Several tests have been carried out by having different people plot linears of the same area. Details differ, but the same main features are always recognizable.

Fig. 25--Simplified geology of Ingray Lake area; AA and CC are believed to be thrust faults; BB is a fault of unknown nature; DD and EE are conjugate transcurrent faults; FF is sedimentary rock; Y is granite; and the Z's are batholiths; compare with previous figure

Ideas develop slowly and are difficult to check during reconnaissance mapping of unsettled country so that it is felt that full use was still not made of the map of linears for plotting faults on the published map. Comparison of Figures 24 and 25 shows that besides those faults which were mapped others are suggested by the linears.

The Snare lineament--A great linear, AA, extending north-northeast across the central part of the Ingray Lake sheet is believed to be of particular significance although only shown as a contact and an unconformity on the geological map (see Fig. 2). It is a peculiar contact, since it has been traced in a gentle curve for 100 mi and extends south as far as Great Slave Lake [LORD, 1942]. With minor exceptions close to its trace, which may be due to irregularities and field error in mapping, all the sedimentary and volcanic rocks that lie to the east of it for 150 mi [see HENDERSON, 1941 and 1944] have been classed as Archean Yellowknife group while all to the northwest for 100 mi [see KIDD, 1933 and LORD, 1947] have been classed as Proterozoic Snare group. This contact is also marked by great changes in the directions of linears and by the termination of the Indin Lineament, some of whose faults offset it as is shown in Figure 24. In the field the writer found it to be hidden everywhere by wide swamps and lakes, but the rocks on either side are more highly metamorphosed than usual while the Snare rocks are foliated parallel to it for a width of several miles. When the writer examined it in the field it, it seemed that it was not an unconformity but a high angle thrust fault of major importance dipping steeply west beneath overthrust Snare rocks. Because of its size it is called the Snare Lineament.

If it is a thrust it, it has many similar properties to the great thrust between Lake Huron and Lake Mistassini which separates the Grenville and Timiskaming sub-provinces [DRESSER, 1945; NORMAN, 1936 and 1947; and GEOLOGICAL SURVEY OF CANADA, 1947a]. Both features have quite different successions of rocks on their two sides. In each case the predominant rocks on the side closest to the center of the shield are lavas and greywackes (Keewatin or Yellowknife groups) while the rocks farther from the center of the shield are gneisses, quartzites, and limestones

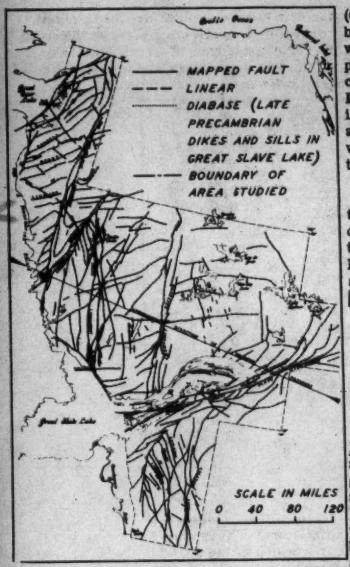

MAPPED FAULT
LINEAR
DIABASE (LATE PRECAMBRIAN DIKES AND SILLS IN GREAT SLAVE LAKE)
BOUNDARY OF AREA STUDIED
SCALE IN MILES
0 40 80 120

Fig. 26--Map of principal linears and known faults in the western part of the Canadian Shield in District of Mackenzie, N. W. T.; the linears were plotted on four-mile to inch maps from oblique air photographs; area is about 500 miles north to south

(Grenville or Snare groups). Both features mark boundaries of metalliferous provinces. For northwest of the Snare Lineament all the mines and prospects are for uranium, radium, silver, and copper [HENDERSON and JOLLIFFE, 1939; and LORD, 1941] while southeast of it gold is the dominant ore mineral. Northwest of the Huron-Mistassini thrust there is a rich area of metallic ores, whereas southeast of it non-metallic minerals are the chief products.

Although it has not been ascertained whether the faults marked BB and CC are high angle thrusts or of some other nature, it is of considerable interest to note that all the important prospects in Ingray Lake area are located close to the intersections of the group of faults DD with the fault CC [see LORD and WILSON, 1942].

SECTION 5

Structural Interpretation of Western District of Mackenzie and Parts of Ontario and Quebec

Linears and structural interpretation of Western Mackenzie District, N. W. T.--The success with which a sketch of linears predicted some aspects of the geology in advance of field work in the Ingray Lake area led G. H. Charlewood and the author to plot the linears of a further 80,000 sq mi of territory, for which oblique air photographs were available lying between Great Slave Lake and the Arctic Coast. Space does not permit the publication of the detailed linears plotted on a scale of four mi to one inch although those for two sheets have already been published [WILSON, J. T., 1941b]. Figures 26 and 27 show the chief linears and also the location of faults already mapped in the field. Attention is particularly directed to those lineaments which are here named after Wop May River, Snare River, Indin Lake, Great Slave Lake, Bathrust Inlet, and Taltson River and the groups of parallel linears named after Camsell River and Rutledge River.

Of all these, the most striking is undoubtedly the Great Slave Lineament which is an important structural feature of the Canadian Shield [for photographs see JOLLIFFE, 1942a]. Its western end in the East Arm of Great Slave Lake has already been mapped by STOCKWELL [1936a and 1936b] who showed it to be a zone of great, nearly vertical faults of late Precambrian age whose southern side was upthrown several thousand feet. Other features that have been recorded [WILSON, J. T., 1941b, p. 498] are that it may be traced on photographs for 400 mi; that the strike is very straight at 60°-240° True; that it is probably a hinge fault with the northern side upthrown at the eastern end; that there is slight field evidence for dextral movement on the branches; and that there is splaying or horsetailing in the northeastern and southwestern quadrants. All these observations suggest, following criteria of Anderson, that the lineament is a great dextral transcurrent fault. It probably has a horizontal right-handed displacement of many miles. The only direction of maximum pressure that could have produced it would have been along a direction somewhere between 85°-265°, and 105°-285° True. Movements along this fault no doubt continued for a long time, but a major part of those movements occurred after the deposition of the Et-then sandstone of supposed Keweenawan age and before the late Precambrian sills and dikes of diabase that lie to the northwest of the fault. Later slight movements along this fault-zone may have been connected with the deposition of lead and zinc ore at Pine Point on Great Slave Lake along the western extension of the fault.

Parallel with this great fault and having other features in common with it are the Camsell group of linears. These are a large number of straight parallel features lying between the north arm of Great Slave Lake and Hornby Bay which is in the northeast corner of Great Bear Lake. All strike about northeast. Most lie between the edge of the Paleozoic cover and the Wop May lineament, but a few extend further east across the Ingray Lake sheet.

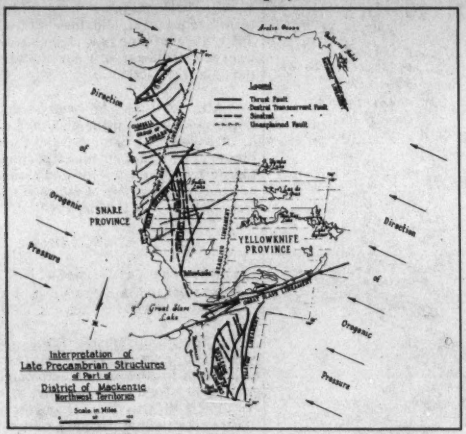


Fig. 27--Interpretation of Figure 26; in the ruled Yellowknife Province gold deposits predominate; northwest of the Snare lineamant (thrust?) there are Snare group rocks containing copper, silver, and uranium deposits

Several of these linears are known to be faults which were formed before the latest Precambrian dikes, but after all other Precambrian formations that are exposed. One of the most northern, the Hornby Bay fault [see JOLLIFFE, 1942a for photograph], cuts the Upper Proterozoic Coppermine series, while late diabase dykes and giant quartz veins have been emplaced along many of the linears. KIDD [1933], LORD [1942 and 1947], and JOLLIFFE [1942a] have shown that the north side moved east on several of these faults so that they appear to be dextral transcurrent faults contemporaneous with and hence probably due to the same forces as the Great Slave fault zone with which they are parallel.

The large sinistral movement of the Indin fault zone, of which West Bay, Akaitcho, Martin faults, and other faults at Yellowknife and at Indin Lake are members, has already been noted. These are of late Precambrian age since they cut large diabase dikes supposedly of that age [CAMPBELL, 1947]. The direction of strike, which is approximately NW-SE, is that which should occur in sinistral transcurrent faults complementary to and formed by the same orogenic pressure as the dextral faults just described.

Approximately parallel with this fault zone are the Bathrust lineament and the Taltson group of linears both of which probably are faults. The Bathrust Inlet area is little known but it was apparently disturbed in late Precambrian time [O'NEILL, 1924; and WASHBURN, 1947]. The rectilinear aspect (straight strike) of the topography suggests a horizontal direction of movement rather than normal faulting. It has been supposed that the Taltson linears are tension cracks, but their straight strike again suggests horizontal movement while two offsets along a belt of gneiss at 110°25'W, 60°55'N, and 111°25'W, 61°00'N [HENDERSON, 1939; and WILSON, J. T., 1941a], show possible sinistral movement.

Between the Arctic coast and Lake Athabasca there are thus five groups of known or suspected fault zones or groups of parallel faults all of late Precambrian age which can all be explained as transcurrent faults due to a maximum orogenic pressure acting along a direction approximately 105°-285° True.

Orogenic forces great enough to produce such large and widespread transcurrent faults might be expected to produce folds and thrusts. If so they should strike about NNE. It is believed that there is evidence of such structures in two places. The suggestion that the Snare lineament may be a major thrust has already been made.

The Taltson lineament shown in Figure 8 is similar to the Snare in several respects. Its trace is likewise hidden by lakes and muskegs but it extends for 200 mi from the Great Slave lineament south to Lake Athabasca. For the most part its path is through granites and gneisses which appear to be more highly metamorphosed close to it. Nonacho sedimentary rocks are folded with axes parallel with it on the east. It also may be a high angle thrust fault, which explanation occurred to the writer when he mapped part of it in the field. The strike of both thrusts is slightly east of north so they could well be due to the same orogenic forces as the transcurrent faults.

A number of major structural features lying between Lake Athabasca and the Arctic Coast have now been described and their origin explained in terms of a single late Precambrian orogeny. It should not occasion any surprise that many of the most conspicuous features should thus be fitted into a single uniform pattern, nor should it be supposed that there are not other earlier orogenies in this region. The forces here postulated do not suffice to explain the complicated folding of the Yellowknife group which is no doubt due to some earlier mountain building for which the evidence has not yet been collected. It is natural that the latest movements should be the most conspicuous and best preserved. The old faults have either been followed by later movements or so sealed as not to be easily eroded to form linears.

A late Precambrian age has been assigned to this orogeny because the flat-lying Coppermine, Et-then, and Athabasca sandstones are the only rocks not extensively folded by it. In part they have been cut by its later movements (indeed at Pine Point there is evidence of slight adjustment even in post-Devonian times) but for the most part these sandstones which are widely distributed in the northwestern part of the Shield no doubt represent detritus which was worn from these mountains as they formed and which was disturbed by the later phases of the orogeny. The Old Red Sandstone bears a similar relation to the Caledonian mountains of the North West Highlands of Scotland. During the mountain building and perhaps at several different times swarms of diabase dikes were intruded in all parts of the area. In some places their accompanying sills and flows have been preserved. These basic rocks form the latest series of Precambrian rocks in the region.

This proposal of a major orogeny in late Precambrian time somewhat strains, though it does not necessarily deny the usual division of the Precambrian into Archean and Proterozoic periods, for it suggests a major division during the later period. The theory that has just been outlined for a large area in the Canadian Shield is a tentative one. No doubt it is much too simple and in parts it may be wrong. Favorable evidence has been stressed, but there are some features not yet explained. The character of Wop May and Beaulieu lineaments is not known. The latter apparently forms the eastern border of a graben of Yellowknife rocks extending to Yellowknife Bay. The angle which all the sinistral and dextral transcurrent faults make with the major pressure axis is far more than the 25° that Anderson postulates. It is about 45°. The Rutledge and Camsell groups of linears are followed by diabase dikes and have some of the characteristics of tension cracks rather than transcurrent faults.

In spite of these uncertainties it is considered valuable to advance the idea that the structure of large areas may be relatively simple in contrast to the complexity of local details. In this large area the broad structural pattern has been shown to indicate a uniform history for the Proterozoic era. If this thesis can be maintained, it represents an advance over separate detailed descriptions for each locality and will give clearer meaning to Precambrian age terminology at present used so loosely.

Preliminary study of linears and structure of a region along the Ontario-Quebec Boundary--Unlike the previous section which was based upon field study as well as an examination of air photographs, this section is based chiefly upon a study of topographic maps and a compilation of geological work by others. It is therefore of an even more tentative nature. Examination of air photographs in many parts of the Shield has made it clear that many linears are followed by creeks, rivers, and lakes and that linears are not often dry valleys for long stretches. It is hence possible to make a preliminary sketch of linears by using only the drainage pattern as shown on the National Topographical Series maps, eight mi to the inch. This was done for the area surrounding the important group of mining camps at Timmins, Kirkland Lake, Cobalt, and Sudbury in Ontario and Noranda and the gold mines to the east of it in Quebec. The results of this together with the position of established faults and a sketch of the geology are shown in Figures 28 and 29.

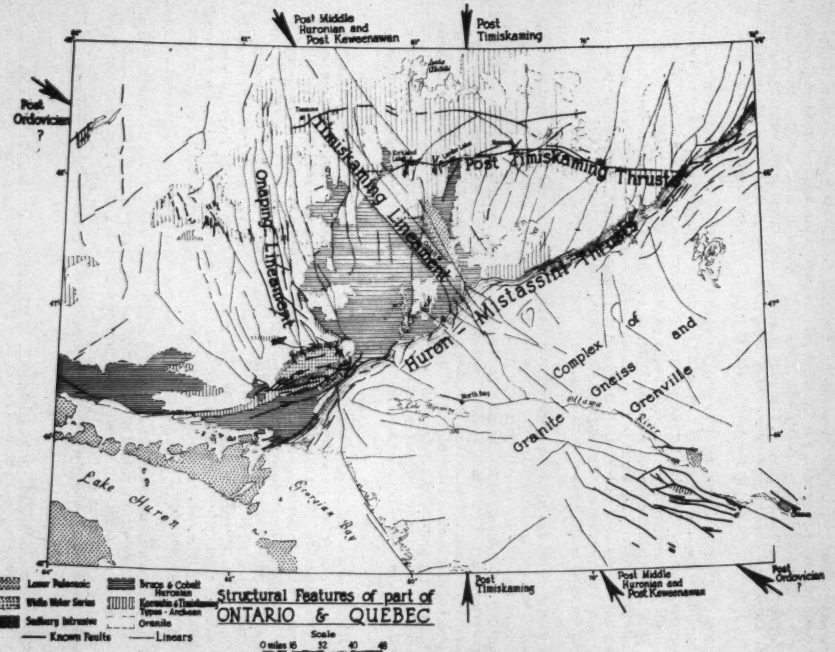
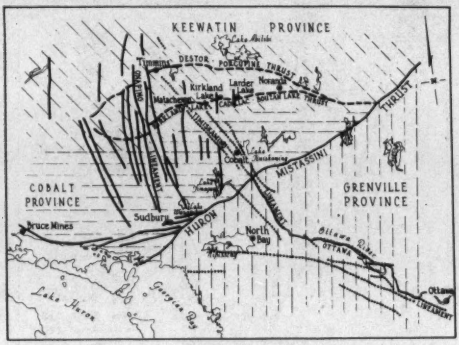


Fig. 28--Map of principal linears and known faults in an area of 95,000 sq mi in Ontario and Quebec; they are believed to be of at least three different ages; the linears were plotted from topographic maps; eight mi to the inch

Post-Huronian orogeny--The most conspicuous feature is the contact between the Grenville sub-province and the Timiskaming sub-province [WILSON, M. E., 1939a] which is marked by many curved linears. It has already been recognized by several [DRESSER, 1945; NORMAN, 1936 and 1946; COOKE, 1946b; and GEOLOGICAL SURVEY OF CANADA, 1947a] as a great thrust of post-Huronian (post-Cobalt) age. The dip is about 55°S in the district south of Sudbury, and the south-eastern side has apparently been thrust up relative to the northwestern side. The Grenville complex represents the eroded roots of an ancient mountain range, while the region to the northwest was at that time a plain in front of the mountains upon which Huronian rocks were deposited as detritus from the rising mountains. It is noteworthy that late Precambrian flat-lying rocks in eastern Ontario and western Quebec only occur relatively close to and along the north side of this thrust (at Lakes Chibougamau and Mistassini, Sudbury, and Sault Ste. Marie). Strength is given to this interpretation by the recent paper that points out that the Adirondacks lie on the south limb of the anticlinorium [ENGEL, 1946]. Presumably the rocks there represent the other side of the ancient range.



Interpretation of Structural Features of Part of Ontario & Quebec

Scale in Miles

Legend

Post-Timiskaming Thrusts

Post-Cobalt Thrusts & Faults

Post-Silurian Faults

Fig. 29--Interpretation of Figure 28; the Keewatin metallogenic province contains gold deposits; the Cobalt province contains copper, nickel, and silver, while the Grenville province contains few metal deposits in this area

If this is so, the Grenville rocks are not so much distinguished from other Precambrian rocks by a difference in age as by a difference in history. Like the Moine and Dalradian schists of the North West Highlands which cannot be correlated with the Lewisian and Torridonian rocks in front of the thrust [PEACH and HORNE, 1930], so the Grenville rocks cannot be surely correlated with the Keewatin, Timiskaming, or Huronian rocks, although they might be contemporaneous (or in part older). No doubt their lack of conspicuous basic lavas and their abundance of crystalline limestones (near the St. Lawrence, but not near the thrust) bespeak a different history before the mountains rose.

The Grenville thrust contact is very similar to that between the Snare and Yellowknife groups. There is the same sharp difference in metallogenic provinces and in rock types. The similarity strengthens belief in the validity of the interpretation of the Snare lineament as a major thrust fault.

The pressures that must have caused this great thrust or thrusts must have been uniform over great distances for a long time and must have been a maximum in a direction normal to the thrusts, that is at about 145°-325°. Thus they might be expected to have produced sinistral transcurrent faults in about a 170°-350° direction and dextral transcurrent faults in about a 120°-300° direction.

The sinistral transcurrent faults appear to be well developed especially in a group of parallel linears here called the Onaping lineament extending north from Sudbury. Attention was first directed to these linears by COLLINS [1917, pp. 16-18] who suggested when mapping the Onaping area that they might be faults. He also indicated a less well developed system striking ESE-WNW to SE-NW which may be the complementary dextral group. From the appearance of linears and existing maps it seems that a parallel series of approximately north-south faults extends from the Sudbury Basin and Lake Wanapitei northwards across the Onaping [COLLINS, 1917], Makwa-Churchill [LAIRD, 1934], Three Duck Lakes [LAIRD, 1932] and Grassy River [GLEDHILL, 1926] map sheets to pass immediately west of Timmins. The traces and offsets of the faults are disguised by drift and different scales and legends on these sheets and they have not been shown on compilations.

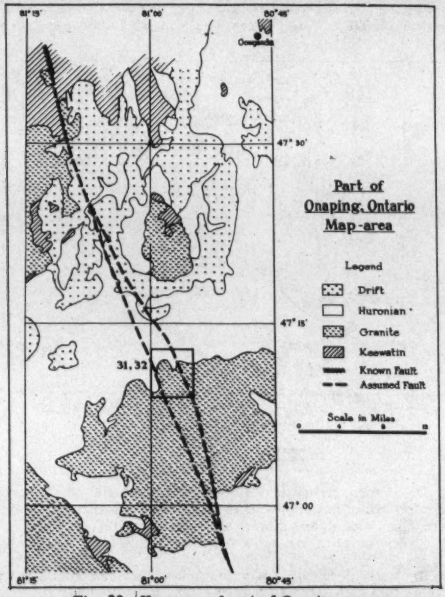


Fig. 30--Key map of part of Onaping area, Sudbury district, Ontario

A splendid example of the value of linears in suggesting the existence of faults from older geological maps is provided in the Onaping area immediately west of that part of it in which Collins suggested north-south faulting. A study of the Onaping and Makwa-Churchill map sheets suggested that a north-south fault or faults with a total of four mi horizontal displacement should cross the contact of Cobalt rocks and granite in the area illustrated in Figure 30. A known fault at the top of the map and an offset at the south suggested the presence of a transcurrent fault with four-mile displacement which has not been shown on published maps; linears suggest the course of the two branches, and the two following photographs show the interpretation across the decisive contact. It must be remembered that the original mapping was of a reconnaissance nature on a scale of four mi to the inch in difficult country and that the line of contact shown on the published map is indicated as being only approximate. A mosaic of vertical air photographs of part of the same area is shown on Figure 31. Stereoscopic examination of these indicated those linears that have been plotted on Figure 32. At once it becomes apparent that two S-shaped curves in the contact could be slightly redrawn to form Z-shaped offsets along three of the principal linears with displacements of one, three, and one-fourth mi, respectively. These displacements

total four and one-fourth mi which corresponds closely with the four mi displacement farther south but indicates that the fault has in this locality divided into one major and at least two minor branches. They apparently rejoin again to the north. This would meet the indications farther north and south exactly without disturbing the original field observations appreciably. The white strip in the largest lake is one-fourth mi long. A linear believed to be a large transcurrent fault with three mi displacement extends south from the same lake and is followed by ponds, creeks, and muskegs; at least two parallel linears can be seen, one to the right-hand side is believed to be a fault with one-mile displacement.

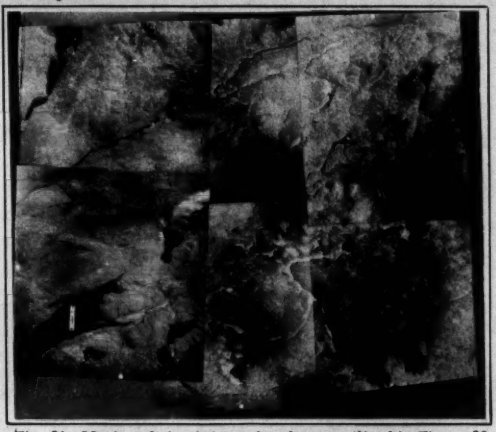


Fig. 31--Mosiac of air photographs of area outlined in Figure 30

This proposal has been discussed with J. J. O'Neill who was Collins' assistant responsible for mapping that part of the area. He agrees that this is quite a possible interpretation and would not conflict with the data he was able to collect in the field during reconnaissance mapping on four mi to one inch scale in difficult country. It is considered that this type of modification of older and reconnaissance maps will have to be made in many cases, and that the new interpretations will not invalidate nor conflict with the careful field work of former workers to any greater extent than in this case.

Thus the individual faults of the Onaping lineament have horizontal movements of up to several mi apiece with the west side moving south in nearly every case so that the whole zone may have many miles displacement. This seems to have led to the Destor-Porcupine belt being displaced southwards west of Timmins to continue in the Ground-Hog area while the Cadillac-Kirkland Lake belt has been displaced to be perhaps continued in the Makwa-Churchill and Three Duck Lakes areas.

These faults are post-Cobalt in age but are older than the Sudbury intrusive, although a revival of movement in the same direction did slightly offset the north side of that body [COOKE, 1946a and 1946b]. Cooke has shown that that intrusive is younger than the Huron-Mistassini thrusting, so that the Onaping faults must be nearly contemporaneous with the thrusting. It seems probable that the Sudbury intrusive and its associated ores were emplaced at the junction of these two sets of faults in a manner emphasized by BILLINGSLEY and LOCKE [1939].

One indication of the state of crustal stresses in the time following the orogeny that formed the Grenville Mountains is given by the major Abitibi dikes mapped by NORMAN [1946] and others. These extend for a great distance across Quebec and north of and parallel with the Huron-Mistassini thrust. There are indications on the Gowganda and Bryce-Robillard map-sheets [BURROWS, 1926; and MOORHOUSE, 1941] that they may extend under the clay belt into Northern Ontario also.

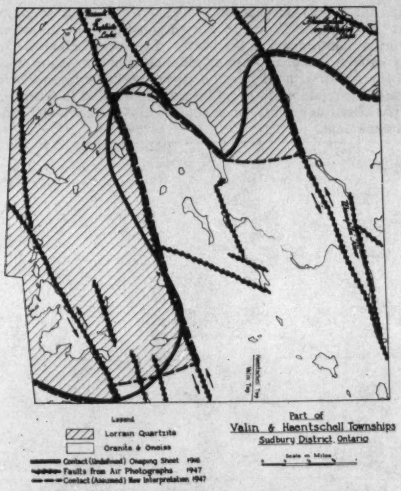


Fig. 32--The jagged lines are linears plotted from the mozaic shown in Figure 31; they have been interpreted as faults and the contact changed from the curved to the dashed line, thus allowing these faults to take up the necessary displacement

At first thought it seems peculiar that these great dikes strike in the same direction as the thrusts and not at right angles and parallel with the direction of maximum orogenic pressure. However, it seems to be a characteristic of mountain building that it so completely relieves the stresses that cause it that the direction of major stress during the orogeny becomes a direction of relief of pressure during the following period. Other examples are the Devonian and Borcovician dikes which RICHEY [1939] and ANDERSON [1942] show to have immediately succeeded the Caledonian and Armorican orogenies and which, like those of Abitihi, are parallel with the thrusts and folds of the mountains rather than at right angles to them.

The Burrows-Benedict fault at Timmins, which is post-ore [HURST, 1938], is a branch of the Onaping lineament, and other parallel faults of the same probable age and cause occur widely. Probable examples are the post-ore faults in Kirkland Lake and Larder Lake areas [THOMSON, 1945 and 1947] and the large fault along the Agawa Canyon north of Sault Ste. Marie [BRUCE, 1940; and MOORE, 1931].

It is concluded that north of the great Huron-Mistassini thrusts there are many north-south sinistral faults due to the same forces and that there is a concentration of these along the Onaping lineament, connected with a change in strike of the thrusts at Sudbury.

It should be observed that Anderson's reasoning about the movements to be expected after failure suggest that in any transcurrent fault vertical movements should develop in opposite directions at the two ends. This produces the "hinged-faults" that have been observed. (The theory of the stress or strain ellipsoids applies only at the moment of failure and does not deal with subsequent movements.) The direction to be expected is such that for the southern end of N-S sinistral faults the eastern side should move downwards relatively. This suggests that the large area of Cobalt rocks lying east of the Onaping lineament may be downfaulted along the Onaping faults and hence be in a graben. One characteristic of grabens is that they usually contain basic intrusives and the Cobalt rocks are abundantly intruded by Nippissing diabase dikes and sills. If the Cobalt rocks are in a graben, the portions of the Kirkland Lake-Cadillac-Bouzan Lake and

Destor-Porcupine belts to the west of the Onaping lineament must be eroded to a greater depth than are the parts to the east where the larger gold camps have been found.

The dextral faults are not so well developed, but some were suggested by COLLINS [1917] and appear to extend at about 120° from the Onaping lineament towards Lake Wanapitei. There may well be an important one along the Vermillion River.

These, then, are some features suggested for a post-Huronian orogeny in this region. The copper, nickel, and silver mineralizations and the basic intrusives at Keweenawan Peninsula, Bruce Mines, Sudbury, and Cobalt were connected with its later stages; but the gold ores at Kirkland Lake and Porcupine are clearly earlier, and something can be made out of a possible orogeny with which they were connected (see Fig. 29 for metallogenic provinces).

Post-Archean orogeny--Although the Huronian formations are folded and metamorphosed near the Huron-Mistassini thrusts, they are flat-lying and fresh farther north, even where cut by many later faults. Beneath them are the complex of Archean rocks often known in general terms as Keewatin lavas and Timiskaming sedimentary rocks. Locally they are divided in other ways and contain much evidence that their true subdivision and history must be complex, but in most places they are folded into steep attitudes, greatly altered, and their structure has not yet been established.

Two important east-west structural features have been traced for great distances since they are easily recognized and economically important. These are two great, faulted, synclinal belts near which lie many gold deposits. The more northerly passing through Timmins is known as the "Destor-Porcupine Fault," the more southerly as Kirkland Lake-Cadillac-Bouzan Lake Fault [AMBROSE, 1944; and NORMAN, 1944]. They have many branches and parts of them have not been traced, but to the east they appear to be connected. To the west they have been less well mapped, but the suggestion has been made that they are bent southward by horizontal movement along faults in the Onaping lineament and they may continue and join together in the Swayze area [BURROWS and HORWOOD, 1938].

With regard to their nature there is also uncertainty. There does not seem to be any reason to suspect that such great features should be normal faults, and their curved path rules out their being simple transcurrent faults. Therefore unless they have undergone motions too complex to be classified, they seem likely to be thrusts [HOPKINS, 1947]. Some local horizontal motion that has been observed does not prevent thrusting having been their main motion, while the fact that folding has been parallel with their strike suggests it.

Their very steep dip is certainly not conformable with Anderson's views upon thrusting but those may apply only to thrusts developed near the surface. It seems quite possible that thrusts steepen with depth and that the Anderson premises no longer hold for the roots of thrusts formed at great depths and subsequently exposed. On the other hand, the synclines of infolded sediments along these breaks and the intrusion of small periodotite bodies along them suggest the idea of Hess [1938] that these belts may be part of former deep down-folds of the crust or "tectogenes." In our present uncertainty it only seems possible to suggest that the faults are thrusts and that they and their associated folds were formed by maximum pressures acting along a north-south axis at an earlier time than the northwest-southwest pressure that formed the Huron-Mistassini thrusts.

Post-Precambrian faulting--Besides the movements just discussed there are others which displace Lower and Middle Paleozoic rocks near Lake Timiskaming, Lake Nipissing and Ottawa. These are not associated with any marked folding of either the Paleozoic or of Huronian rocks so they cannot represent another orogeny in this region. They may be outlying effects of the Appalachian orogeny or they may be associated with epeirogenic uplift perhaps in part as recently as Pliocene [COOKE, 1931]. The most conspicuous of these faults is the group here known as the Timiskaming lineament extending from the Ottawa River south of Lake Timiskaming northwestward as far as Timmins. Their very straight strike suggests that they might be transcurrent faults except that there is little horizontal movement along them. There is at most a few hundred feet displacement at Timmins in that fault which passes up the Montreal River and reaches South Porcupine by a valley followed by a power line [HURST, 1938]. It seems that the main area of Cobalt rocks is terminated eastward by these faults which suggests considerable vertical movement along some of them. Although they displace Ordovician and Silurian rocks, it appears that Cobalt and South Lorraine silver camps both lie on the same one of these faults, while the Round Lake and Watabeag Lake granite batholiths also appear as though they might be connected with the lineament. This implies that this zone of weakness may be much older than post-Silurian in age. The writer is at present studying this zone for the Ontario Department of Mines.

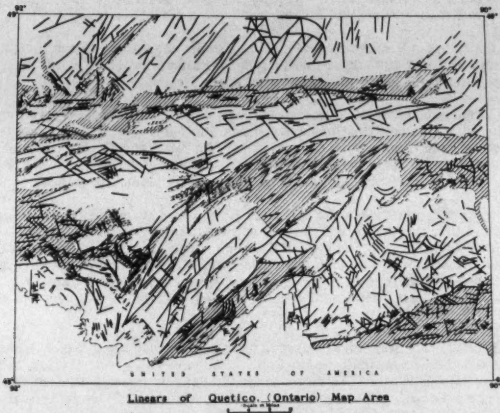


Fig. 33--Map of Quetico area, Ontario, showing linears plotted from air photographs; they follow the direction of folding in sediments; AA follows a Keewatin-Couchiching contact and may be a fault

Linears and structure west of Lake Superior--It seems probable that the disturbances that occurred northeast of the Great Lakes continued westward. Norman at one time held the view that the Huron-Mistassini thrusts may have in part continued along the north shore of Lake Huron across Lake Superior and were connected with the great faults known to exist along Keweenawan Peninsular and southwest of Duluth (oral communication). TYSON [1945] has suggested that other faulted belts occur northwest of Lake Superior that are similar to the gold-bearing belts of post-Archean age that cross the Ontario-Quebec boundary.

These ideas have not been examined except in the Rainy Lake area already referred to (see Fig. 11) and in the Quetico area for which G. H. Charlewood plotted the linears from oblique air photographs (see Fig. 33). They were then compared with the geology shown on the Quetico sheets [TANTON, 1938 and 1940]. The greatly simplified sketch of this shown on Figure 33, indicates that the linears follow the elongated beds of sediments and curve around the granitic intrusions. The prominent linear AA precisely follows the contact between the Couchiching and Keewatin, suggesting that it may be perhaps a fault contact.

It also seems likely that parts of the shores of Lake Superior are controlled by faulting in the same way that the Huron-Mistassini thrusts and Onaping lineament extension control the shape of Lake Huron (see Figs. 28 and 34).

Late-Precambrian Orogeny in Labrador--In addition to these major distrubances in the Great Lakes region there appears to have been another in central Ungava. GILL, BANNERMAN, and TOLMAN [1937] have shown that the great thrusts which are recognized to extend from Lake Huron to Lake Mistassini probably continue with the same strike towards central Ungava. Still farther northeast on the Labrador boundary RETTY and MOSS [1947] have shown that there is more folding and thrusting but in a direction almost at right angles. The relation is shown on Figures 16 and 34 which indicates that northwest-southeast striking disturbances of central Labrador or Ungava truncate the Huron-Mistassini thrusts and are presumably younger. The iron deposits are curiously enough close to the intersection of these zones.

We have thus distinguished at least three orogenies in eastern Canada. Of the four major divisions deduced, two are perhaps Archean and two are Proterozoic. There was also later faulting not part of a local orogeny. We have no certain means at present of knowing how these divisions should be correlated with those in the Mackenzie District of the North West Territories. If the post-Cambrian orogenies of eastern and western America are any guide, it seems quite possible that the divisions of the eastern and western Precambrian are not of the same age.

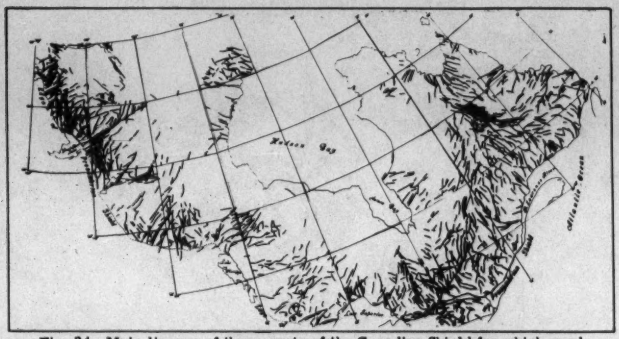


Fig. 34--Main linears of those parts of the Canadian Shield for which good topographic maps are available; the linears were drawn from those maps

SECTION 6

Suggestions Concerning the Growth and Structure of the North American Continent

The symmetry of the North American continent is well known. It consists of a large and central shield area, over much of which Precambrian rocks are exposed. There are four systems of mountains around the Shield, cut out of later sedimentary rocks, in each case folded tangentially or parallel with the margins of the Shield (see Fig. 35).

The Appalachian Mountains folded in late Paleozoic time and the Cordillera of Mesozoic and Tertiary age are well known. Their inner margins are thrust over the covered Shield. The fact that these mountains form a V or U-shaped margin to the Shield has often been mentioned as has the similar arrangement of the foliation within the Shield [WILSON, M. E., 1939a]. Less studied, but comparable in size with the Appalachians, are the East Greenland Mountains and those that cross North Greenland and Ellesmere Island. The former range was nearly 1000 mi long, with peaks 13,000 ft high. It consists of early Tertiary volcanic rocks and of sedimentary rocks folded during the Devonian period [TEICHERT, 1939]. The later range, although 700 mi long and reaching 11,000 ft altitude in places, has been so little examined that even the age of the main folding is still unknown. When these northern mountains are considered, it can be seen that the continent has the shape of an irregular polygon rather than a U or a V.

The orogenic forces that produced these successive additions around the margins of the continent must presumably have acted inwards towards its center.

It is here suggested that the same radial and inward forces acted to form tangentially folded ranges of mountains during Precambrian time as have acted since. Some of these ancient ranges are shown diagramatically in Figure 35, while their residual roots can be visualized on the geological map of Canada [GEOLOGICAL SURVEY OF CANADA, 1945]. In the former the succession of ranges is shown numerically, but three western ranges have not been correlated with the others and so are lettered. Other Precambrian ranges no doubt exist.

Linears of the Canadian Shield--Having carried observation and speculation so far beyond the limits imposed by field work, one further generalization has been essayed by the use of linears. With the aid of A. Kastner, linears were marked in crayon on about 500 topographic maps made from air photographs which comprise most of the maps available for the Canadian Shield on the scales two, four, and eight mi to the inch. These linears were transferred to the eight-mile scale and reduced to a scale of 32 mi to the inch photographically. (The two-mile and four-mile scales were used where available as they show details not reproduced on eight-mile maps.)

The resulting map is a maze of linears in which some fault linears and the circular foliations in some areas of granite and gneiss stand out plainly. A very much simplified reproduction of the main features is given in Figure 34. The concentration of linears towards the margin of the Shield

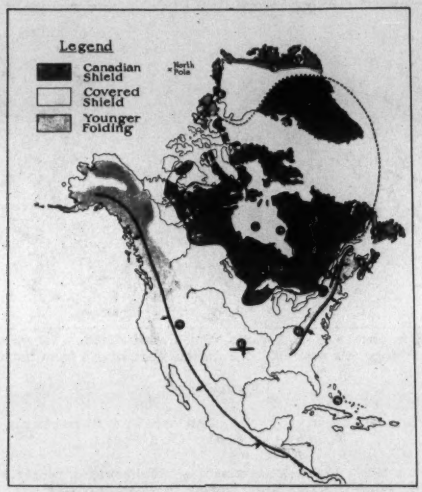


Fig. 35--Sketch map of North America showing six known and major orogenies built around the Shield and at least five within it

is chiefly due of course to the fact that the best and most detailed maps have been made of the more accessible parts. It may be partly real, however, since the margins of the Shield are generally higher than the interior so that linears would show up best in those parts which had been more elevated and eroded.

Some striking features of the pattern are worth mentioning and serve to summarize our conclusions.

In the northwest, among the Mackenzie Great Lakes it has been shown that folding (B on Figure 35) with a NNE strike and many large faults may be explained by a late Precambrian orogeny whose major forces acted along an axis extended from WNW to ESE and which passed through Hudson Bay in the center of the Shield. This was preceded by an as yet undescribed orogeny (A).

Across western Quebec and all Ontario northwest of the Grenville region are a series of east-west belts of sedimentary and volcanic rocks, folded and in some cases thrust as though by forces acting along a north and south direction and again radial to the Shield. This orogeny (1) was of Archean age.

To the west the belts of this series stop abruptly along the valley of the Nelson River which is thus revealed as a very ancient line of weakness. The pattern is then confused until a marked northeast-southwest parallelism of structure and some north-south fractures in northern Saskatchewan and in the District of Keewatin suggests an ancient and tremendous pattern of shearing. The implications of this have not been investigated and until more is known it is only possible to say that the structures are such as to make a wide and complete break between east and west. We thus cannot be sure at present whether eastern and western orogenies were contemporaneous or not.

Further east in Ontario and Quebec it has been suggested that a great range (2) once extended parallel to and over the St. Lawrence valley and that it was bounded on the north from Lake Huron to the center of Labrador by a great thrust dipping south under the range. The east-west striking Archean belts were truncated by it while beyond it they were broken by many large transcurrent faults. Within the range the rocks were metamorphosed into the Grenville series. This orogeny

may also be the cause of some of the great faults found striking southwest in Minnesota and other thrusts which are suspected to exist nearby just north of the Canadian border. This range was also tangential to the core of the continent and thrust up on to it. The major forces that produced it acted along a northwest-southeast direction, again passing through the center of the Shield.

In central Ungava a still later orogeny (3) again thrust inwards and upwards onto the Shield. Farther north in the Arctic, very little is yet known of the relations of the bordering mountains to the Shield.

Thus the area (X) hidden by Hudson Bay is suggested as the core of the continent about which successive geosynclines and ranges of Precambrian and later ages have been piled.

This view agrees with the idea that the Earth is contracting, which has often been expressed and most recently restated by SONDER [1947]. He mentions that the shield areas are intermittently rising as a result of this contraction and that geosynclines should often form around the margins as a result of deposition of material eroded from the rising continents. While the writer acknowledges his debt to Vening Meinesz, he is not yet prepared to state how the linear pattern of the Canadian Shield fits into his pattern of world-wide shear nets [VENING MEINESZ, 1947].

This theory of intermittent contraction and uplift of the continent can be very well fitted to an explanation of the present topography and recent behaviour of the Canadian Shield. Before the Tertiary orogenic paroxysm it is generally agreed that the Canadian Shield was very perfectly base-leveled into a flat low peneplain containing a basin of Paleozoic rocks near its center. The Tertiary disturbances according to Sonder should have caused uplift and a tendency towards contraction in the Shield. These forces evidently did not act uniformly for the margins of the Shield rose all the way round while the center sank slightly to form Hudson Bay. Post-glacial depression may account for Hudson Bay but cannot explain the marginal uplift while the Paleozoic outlier on its shores shows that slight central sinking has happened before. The high marginal hills include the Torngat, Baffin Island, Greenland, and Adirondack Mountains, the Laurentian Highlands, those immediately north of Lake Huron and Lake Superior, and the high ground between the Mackenzie Great Lakes and in places along the Arctic Coast. In nearly all parts there is a long gentle slope toward the low shores around Hudson Bay. The margins of the Shield are in many places faulted, in others apparently only monoclinally folded. It is suggested that the raised margin and depressed interior are due to the margin of the Shield becoming tilted upwards under renewed forces of compression and contraction in Pliocene (?) time.

Conclusions and Acknowledgments

To make a more complete statement of the structural ideas here sketchily advanced, much more information is required. Geophysical information about the third dimension of the crust is needed as well as more field geology. It is encouraging to note that the Department of Mines and Resources has started a series of gravitational, magnetic, and seismic studies of the Shield to that end while the Ontario Research Commission is enabling the University of Toronto to carry out geothermal and radioactivity studies [NATIONAL RESEARCH COUNCIL, 1947].

Though this paper cannot hope to be correct in detail, it is hoped that it will stimulate more interest in structural research upon the largest features of the Canadian Shield. It is considered that this will be fruitful both in scientific knowledge and economic reward. In the latter regard it is significant how many major mining camps, such as Labrador, Porcupine, Sudbury, and Yellowknife occur at junctions of lineaments, as BILLINGSLY and LOCKE [1939] suggested was the case in western United States. The fact that in some camps such as Procupine and Yellowknife one set of faults is post-ore does not invalidate the theory if we believe that both ore and faults followed fundamental lines of weakness.

The assistance of G. H. Charlewood, A. Kastner, A. Aiken, and Miss J. Morice in carrying out this work is gratefully acknowledged, as are the suggestions and advice of many colleagues. The writer would also like to thank the Geological Survey of Canada, National Research Council of Canada, National Air Photograph Library, Ontario Department of Mines, Ontario Research Commission, and the University of Toronto for the support which they have given at various times and in different ways but always in a most helpful manner.

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RECENT REGIONAL GRAVITY SURVEYS

George Prior Woollard

Abstract--This paper calls attention to the vast improvements in design of gravity instruments, states that we are now in position to consider the feasibility of developing a nation-wide gravity network, and discusses the value of such a network. It mentions that gravity data may be secured from oil company surveys for studies from a geodetic standpoint and discusses the progress made and future work planned by government agencies and university groups on gravity determinations.

Introduction--Gravity surveys have been made both for the study of geodesy and the study of geology. From a geodetic standpoint such surveys furnish data for determining more exactly the shape of the Earth and for determining local departures of the vertical. From a geologic standpoint, gravity surveys furnish data for studying the mass distribution within the Earth's crust and for determining the degree to which isostatic compensation is achieved.

As a result of the impetus given to gravity surveying by the search for subsurface oil reservoirs, rapid and very precise gravity instruments have been developed which have made it possible to undertake gravity surveys which 20 years ago would have been regarded as prohibitive both from the standpoint of the time and money required. Whereas it formerly required two days to make a gravity observation which had an accuracy of plus or minus one to two mgal, a reading can be taken with a modern instrument in five minutes which has an accuracy of plus or minus 0.01 mgal. Similarly, whereas a full truck load of equipment formerly was required for making a gravity measurement, the latest modern gravity instruments weigh about five lb and consist of a single piece of equipment about the size of a quart thermos bottle.

In view of these instrumental improvements, it is not surprising to find that large areas of the country have recently been surveyed gravitationally and that for the first time we are in a position to consider the feasibility of developing a gravity network embracing the entire country. Data from such a network of gravity stations covering such a large area and involving so many varied topographic and geologic tectonic provinces would constitute one of the major contributions to basic science as they would permit many scientific investigations to be carried out which up until now have not been possible because of the lack of data or the poor distribution of the available data. From an economic standpoint, the direct value of such data in the search for oil or other mineral deposits would be negligible, although indirectly the results of certain investigations based on such data may be of great value in the future search for ore deposits. This lack of direct economic application of such a survey is related primarily to the small size of oil structures and ore deposits and the need for a very close station spacing in this type of work which would not be economical on a nation-wide survey.

What information would be obtained can best be described through a discussion of the gravity anomalies. After corrections for the shape of the Earth, its speed of rotation, the elevation of the station, and the mass beneath the station down to sea level, the resulting residual value (Bouguer anomaly) reflects the mass distribution within the Earth's crust and is a composite of the effect of the thickness of the crust, lithologic changes within the crust, the near-surface geologic structure, and changes in lithology at and near the surface. The respective parts of the anomaly that may be accounted for by each of the above will depend upon the density, size, and distance of the respective masses. Usually, the primary control of the anomalies is the thickness of the Earth's crust, and the anomaly associated with it is essentially the amount of the isostatic correction. In this country this averages about 40 mgal for the eastern half of the continent to over 100 mgal in the western half, with a peak value of about 300 mgal beneath the Rocky Mountains [WOOLLARD, 1943]. Changes in intra-crustal lithology which may or may not extend up to the surface appear to exert the second largest effect upon the anomalies. These effects are of the order of 20 to 30 mgal and are superimposed upon the broader gravitational effect of variations in crustal thickness. Large granitic bodies commonly have negative anomalies of this magnitude associated with them [MILLER, 1946], and basic masses such as the Adirondack anorthosite massif may have similar positive anomalies associated with them [WOOLLARD, 1948]. Near-surface features of small size, such as ore deposits, basement structures, and rocks with minor

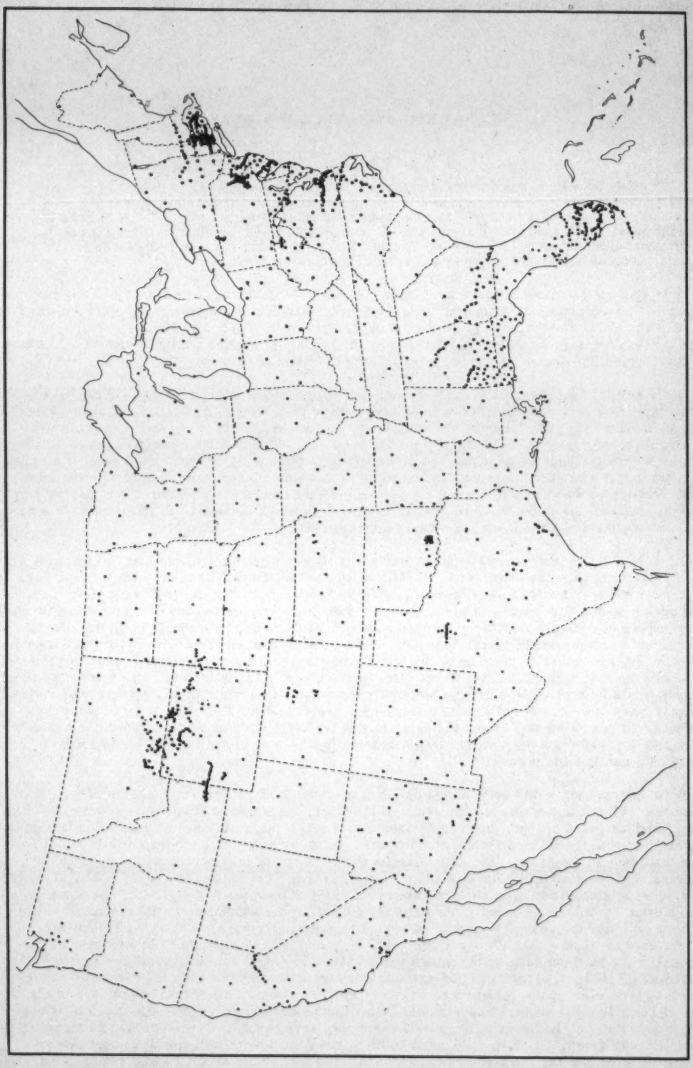

Fig. 1--Distribution of pendulum gravity stations established by the United States Coast and Geodetic Survey

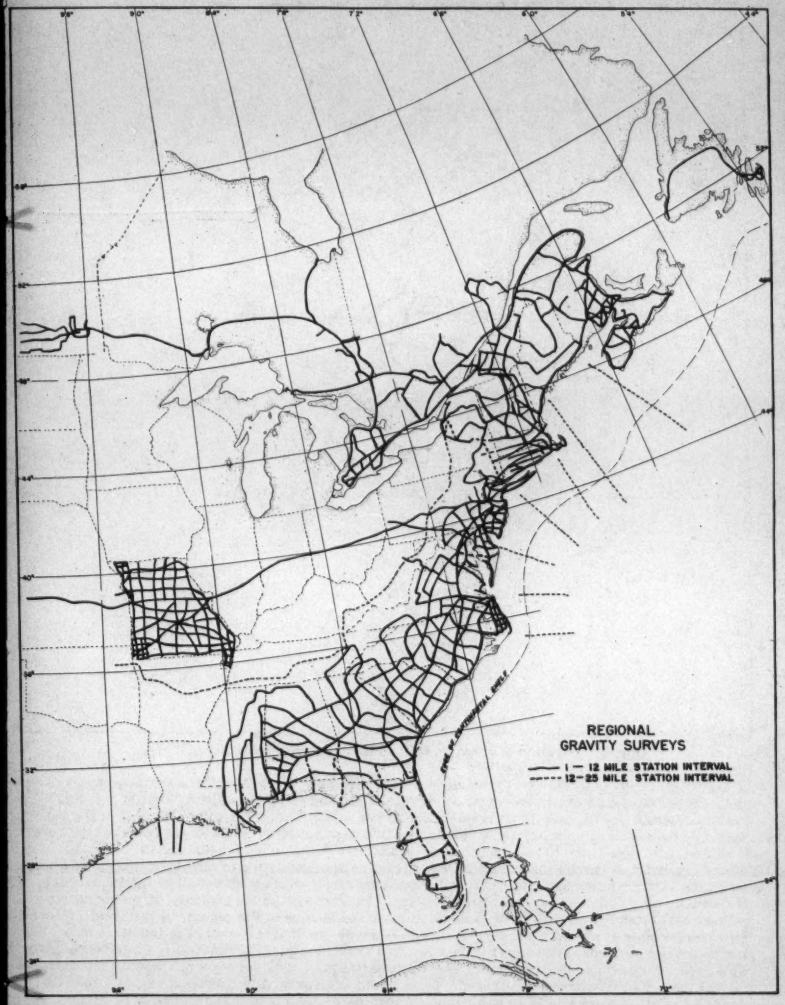

Fig. 2--Location of regional gravity surveys in eastern North America

density contrasts, exert the least effect upon the anomalies. Salt domes, for example, usually have a gravitational effect of about two to three mgal. Some large structures, such as the Nemeha Granite

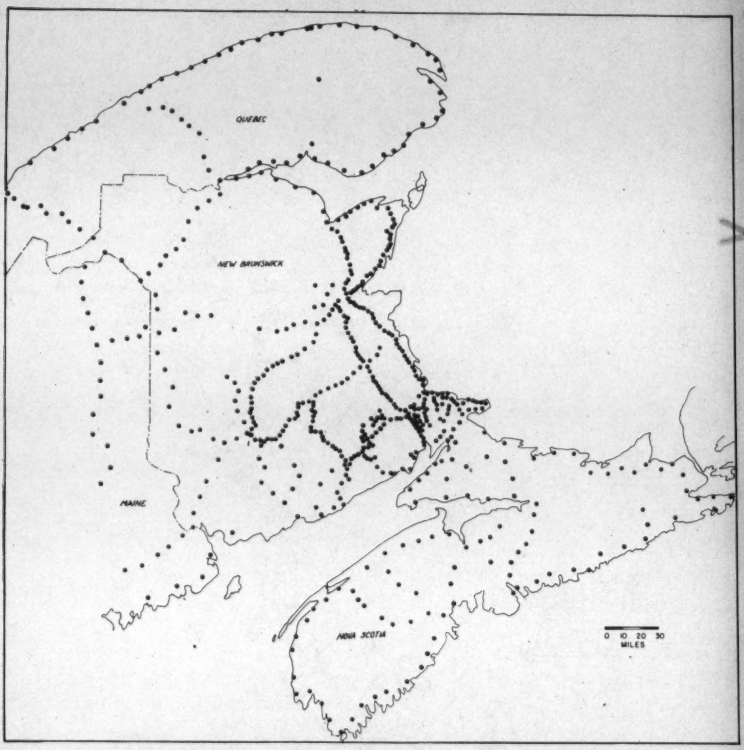

Fig. 3--Location of gravity stations in Maritime Provinces of Canada

Ridge which involves a 5000-ft displacement of the basement rocks in eastern Kansas, have a gravitational effect of only one to two mgal at the localities studied by the writer. Similarly a high-grade economic ore deposit may have only one to two mgal effect when within 100 feet of the surface, and be essentially undetectable if they are 1000 feet below the surface. In commercial work it is therefore necessary to remove arbitrarily the bulk of the anomaly obtained as "regional effect" in order to isolate that small part of the original anomaly which may be of economic significance. On the other hand, this discarded regional effect which contains all of the first-order, and usually all of the second-order gravity effects incorporated in the anomaly, is the most important part from the standpoint of geodetic studies and studies of the geology of the crust. Therefore an oil company having a survey with stations set at one-fourth to two-mile intervals on traverses two or three miles apart is in a position to further geodetic studies by contributing gravity data for stations at eight- to ten-mile intervals over the area of the survey which would adequately reflect the regional anomaly structures. Contribution of gravity data on such a regional basis would be of little or no benefit to competing companies which lacked the closer-spaced data. Actually, in practice, it is found that as a rule the regional anomaly field can be adequately mapped using traverses forming a 20- to 30-mi grid with stations set at eight- to ten-mi intervals. Where local structures are indicated, a closer coverage can be established later.

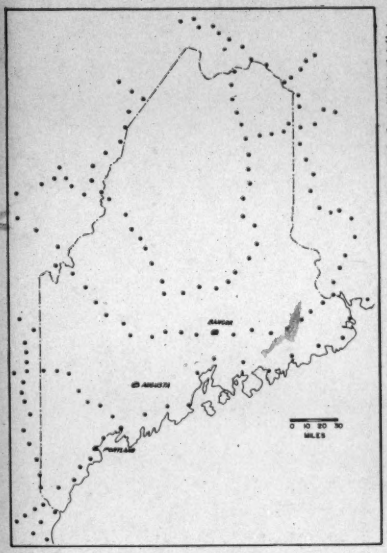

Fig. 4--Location of gravity stations in Maine

Extent of regional gravity surveys in the United States--Oil company surveys--The largest compilation of gravity observations in the United States is that held by the oil companies. These data, accumulated during the past 20 years in the search for potential subsurface oil reservoirs, cover practically all of the mid-continent region, the coastal plain of the Gulf of Mexico, the southern part of the Atlantic Coastal Plain, and many of the inter-mountain valleys of the western part of the country. The total investment of the various companies in these data amounts to several millions of dollars, and this alone should be an adequate endorsement of the geologic value of gravity data. However, as pointed out, the economically significant portion of these observations is confined primarily to the third-order effects which have to be isolated by arbitrarily removing the bulk of the anomalies as regional effect. Since the regional effect has no economic significance, some of the oil companies have been willing to release such data for scientific studies in the areas they have surveyed, and recently the United States Coast and Geodetic Survey has approached most of the major oil companies and exploration companies relative to obtaining such data for the entire area that has been commercially mapped. These negotiations are still in progress, and the prospects for securing all of the data requested appear to be very good.

Government surveys--The United States Coast and Geodetic Survey has been the principal government organization to make gravity surveys in this country and the establishment of a nation-wide network of pendulum gravity stations has been a major activity. This network started in 1896 comprises about 1200 stations at this time. In several areas, notably the Bighorn Mountain Region of Wyoming, southern New England, southern Florida, the coastal region of Virginia and North Carolina, eastern Pennsylvania, and southern Alabama, a sufficient density of pendulum stations has been established to constitute local surveys, but on the whole stations have been distributed on a broad basis as indicated in Figure 1. These stations, originally established because of the information they would yield concerning the shape of the Earth, have also been of great value during the past 15 years as control points for calibrating the gravity meters used on other gravity surveys and as points at which to tie other gravity surveys so that the observations could be put on an absolute basis.

In addition to the gravity work of the United States Coast and Geodetic Survey, the United States Bureau of Mines, and the United States Geological Survey during recent years have made some gravity observations. Most of the gravity work of these two organizations, however, has been confined to detailed surveys covering very limited areas. An exception is the offshore gravity survey made for the United States Geological Survey partly across the continental shelf in the Gulf of Mexico. This survey which starts in the vicinity of the Texas-Louisiana State Line consists of three approximately parallel traverses which run perpendicular to the shore. They extend about half way across the continental shelf. Observations were made using a gravimeter in a diving bell, and stations were occupied at about two-mile intervals.

Other surveys--Although there are several gravity meters now in the hands of various university groups, only two of these groups have been active in making regional gravity surveys. One of these is at Princeton University and the other at Columbia University. The Princeton University group has been using a gravity meter on loan for scientific work to the American Geophysical Union by the Humble Oil and Refining Company, to map regional and local gravity anomalies in order to study their relation to known geologic features. These investigations, financed primarily by grants from the Geological Society of America, have resulted in a transcontinental traverse and in a regional survey of the eastern seaboard from the Maritime Provinces of Canada

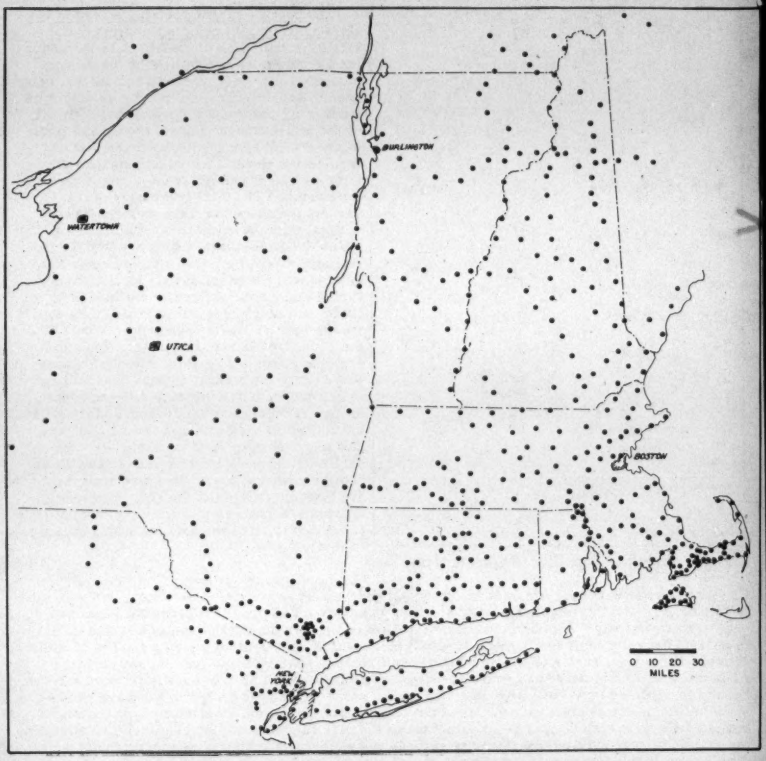

Fig. 5--Location of gravity stations in central New England area

to the Gulf of Mexico [WOOLLARD, 1943, 1948]. On these surveys, stations were set at five- to ten-mi intervals on traverses 20 to 40 miles apart depending upon the road system.

The group at Columbia University has been using a Frost gravity meter which the University owns to carry out a similar program. Work to date includes a traverse with stations at about 20-mi intervals from Tulsa, Oklahoma, to Canton, New York, through the Valley and Ridge Province of the Appalachian Mountains; a traverse across Newfoundland with stations at about five-mi intervals; a traverse in Alaska; and a traverse from Ottawa, Canada, to New York City on which stations were set at about 30-mi intervals. In addition, the Columbia University group has been carrying out an extensive offshore submarine gravity program using Vening Meinesz pendulums on loan from the Woods Hole Oceanographic Institution. This program, supported by the Office of Naval Research and the United States Navy Submarine Service, has resulted in several offshore regional surveys. These include seven traverses across the Atlantic continental shelf between Nova Scotia and Cape Hatteras on which stations were made at about 15-mi intervals; several traverses off the western coast of South America between Panama and Valpariaiso, Chile; a traverse from Panama to Trinidad along the northern coast of South America; and several short traverses off the Bahama Banks on which stations were set at five- to ten-mi intervals. Other regional surveys have been that of Missouri by the MISSOURI GEOLOGICAL SURVEY [1943], one

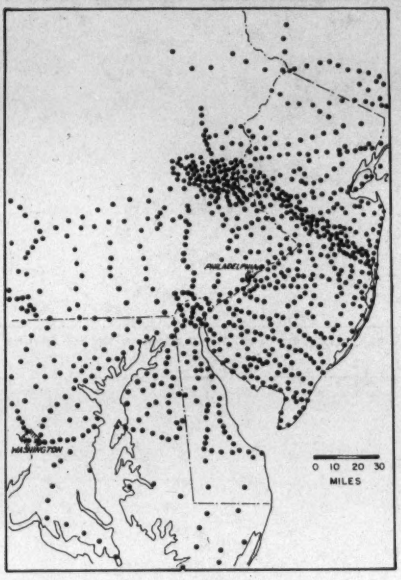

Fig. 6--Location of gravity stations in New Jersey-Delaware area

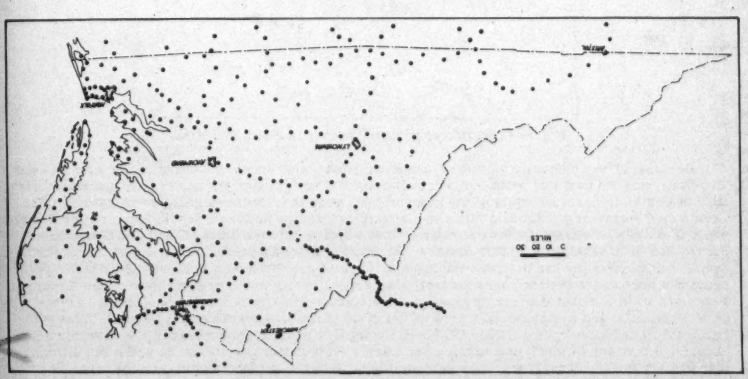

Fig. 7--Location of gravity stations in Virginia

of eastern Pennsylvania by HERSEY [1944], and detailed traverses across the Appalachian Mountains by NETTLETON [1941], and HAMMER and HECK [1941] of the Gulf Research and Development Company.

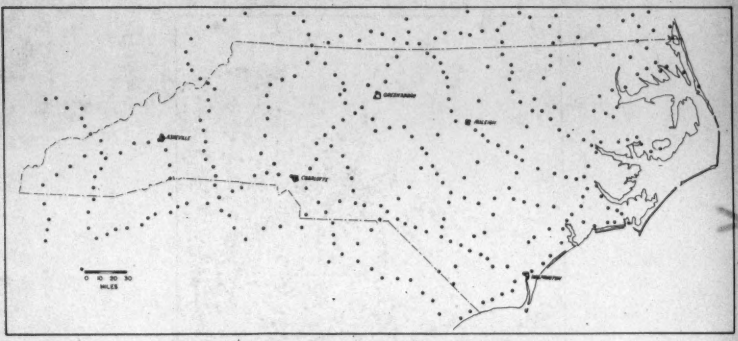

Fig. 8--Location of gravity stations in North Carolina

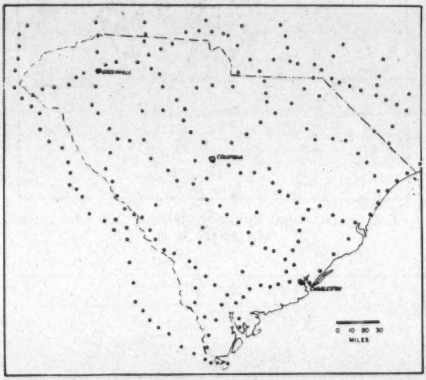

Fig. 9--Location of gravity stations in South Carolina

Because of the proximity of several regional gravity traverses in Canada to the International Boundary, and the fact that neither the gravitation field nor geology recognize political boundaries, it is desirable to consider some of the gravitational work that has been going on in Canada. The Dominion Observatory of Canada since the turn of the century has been developing a regional network of gravity pendulum stations similar to that which the United States Coast and Geodetic Survey has been developing in this country. In addition to these pendulum gravity stations, the Dominion Observatory has been developing a network of gravity meter stations. This latter program has been underway for approximately four years, and up to the present time regional surveys have been completed covering most of the Maritime Provinces, southern Quebec, the Ontario Peninsula, and a considerable area of the great plains region of central Canada. This program was started using the Humble Oil and Refining Company meter on loan to the American Geophysical Union but is now being carried out using a Mott-Smith gravity meter and a North American gravity meter. Traverses are run along highways with one instrument, and the other is transported in a plane to station sites on lakes dotting the back country where there is no road system. The average station spacing on the road traverses is about ten mi. The location of the Canadian gravity traverses in the eastern half of the continent adjacent to the International Boundary and the surveys in the United States for which data are available, or will be when computed

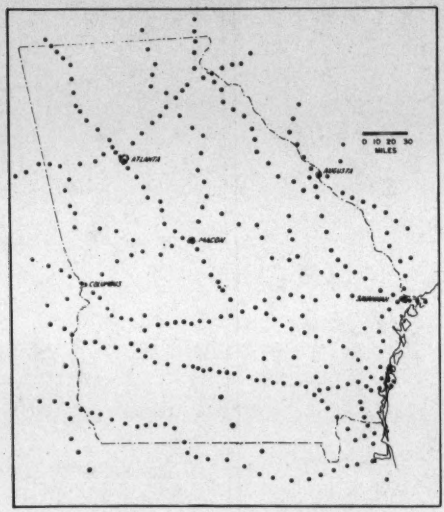

Fig. 10--Location of gravity stations in Georgia

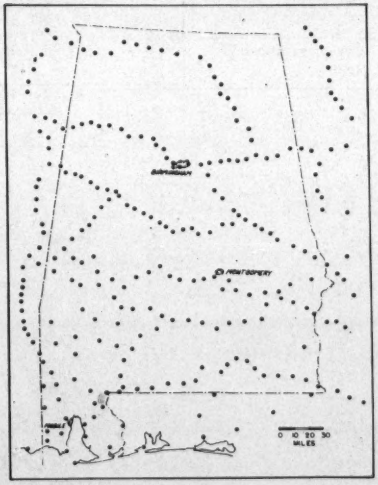

Fig. 11--Location of gravity stations in Alabama

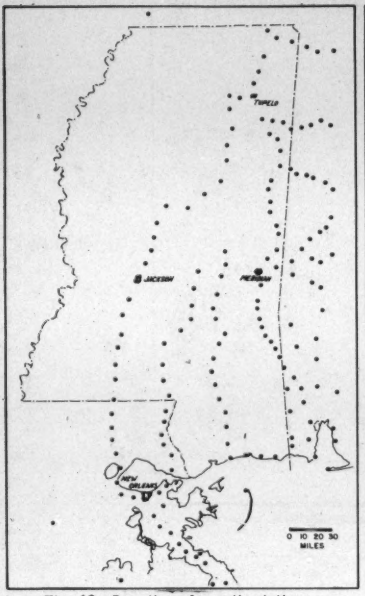

Fig. 12--Location of gravity stations in Mississippi

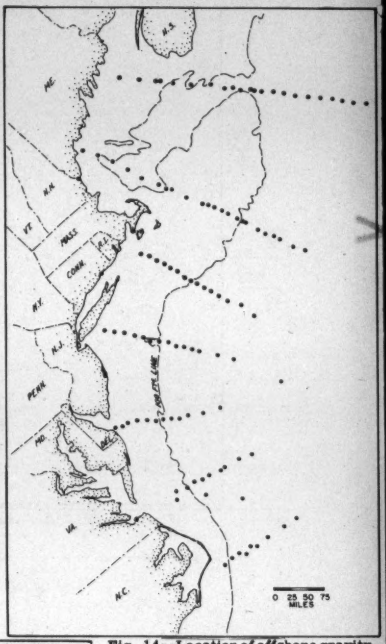

Fig. 14--Location of offshore gravity stations on Atlantic Continental Shelf

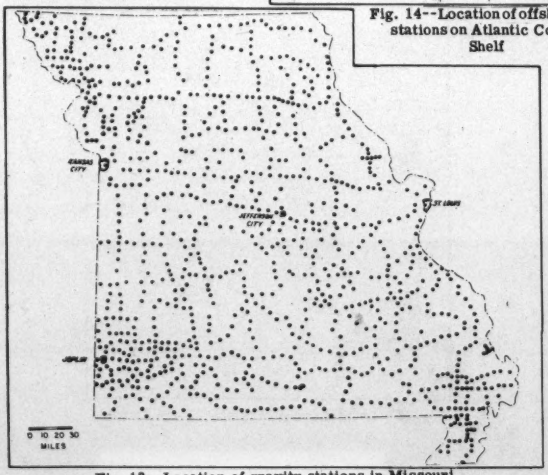

Fig. 13--Location of gravity stations in Missouri

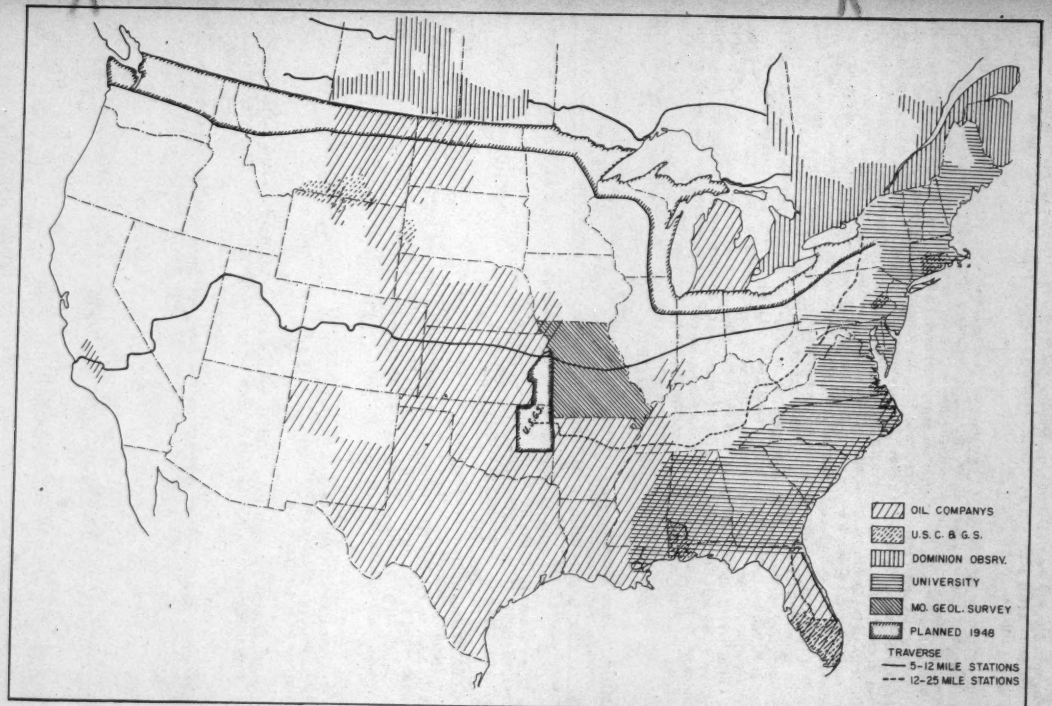

Fig. 15--Schematic map of the United States showing all areas gravitationally surveyed and surveys planned for 1948

are indicated in Figure 2. Detail maps showing the location of stations in those states and areas in which there are a sufficient number of stations to map the regional gravity anomalies are shown in Figures 3 to 14.

Investigations planned for the near future--During 1948 a considerable amount of regional gravity work is contemplated. H. W. Hemple of the United States Coast and Geodetic Survey has advised the writer that the Division of Geodesy of the Survey plans to resume operations on building up the regional network of pendulum gravity stations on which activity was discontinued during the War because of shortage of personnel. H. S. Joesting of the United States Geological Survey has advised that the Geological Survey in cooperation with the United States Coast and Geodetic Survey plans to make a regional gravity meter survey of eastern Kansas and eastern Oklahoma. C. S. Beals of the Dominion Observatory of Canada has written that the Observatory plans to fill in on their regional network of gravity meter stations in Ontario and Quebec, and to extend the network of stations to the west of Hudson Bay. Maurice Ewing of the Department of Geology at Columbia University has advised that his group expects to complete one or more offshore submarine-gravity traverses south of Cape Hatteras over the Atlantic Continental Shelf and will start operations on a network of similar traverses in the northern part of the Pacific Ocean. The group at Princeton University expects to establish a series of gravity meter traverses over a strip about 80 mi wide across the country paralleling the Canadian border. This survey will be tied to the border surveys in Canada and will form a nucleus of stations across the middle of the continent which will permit regional gravity anomalies to be traced on and off the exposed crystalline complex of the Canadian Shield. The general relation of the areas covered to date by all groups and those which are planned to be surveyed in 1948 is indicated in Figure 15.

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DISCUSSION OF "REFRACTION OF SURFACE WAVES BY CURRENTS" by J. W. JOHNSON

[Trans., v. 28, pp. 867-874, 1947]

I. D. Isaacs (University of California, Berkeley, California)--Johnson introduces the subject of refraction of surface waves by currents. This writer has observed these phenomena qualitatively on many occasions and under varying circumstances. The effect of ebb and flood currents in entrance channels to estuaries is marked. During the winter at many harbors on the northern Pacific Coast the entrance channels rarely are passable during the ebb. The bar requently may be negotiated only at the last of the flood, this being the optimum condition of depth and wave refraction by currents. In this connection the following are typical extracts from sailing directions [U. S. COAST AND GEODETIC SURVEY, 1942]:

> The most favorable time for crossing the bar is on the last of the flood current, and on many occasions it is passable only at this time [p. 194].
>
> With wind and swell against the current, short, choppy sea is raised near the entrance to the strait [p. 255].
>
> The heavy broken seas are probably due to the shoaling off the entrance, the irregularity and velocity of the currents, and the conflict between the wind drawing out of the strait and that along the outer coast [p. 257].

It is thus seen that these effects have been noted by navigators and recorded for guidance.

The effect of currents in altering the velocity of propagation of waves is noted in GREAT BRITAIN [1944].

This writer has observed the effect of currents in the refraction of waves many times. The most conspicuous effect is the production of breakers on entrances by the ebb currents. On various entrances of the coasts of California, Oregon, and Washington he has observed that when a heavy westerly swell existed, entrances would be impassable during the ebb and greatly moderated or completely passable during flood currents. This effect was observed to take two forms. In the first case, steep, short-period waves generated by the action of local winds and almost at their limit of steepness were seen to break as soon as an opposing current was encountered. In this case all portions of the tidal stream were affected and short-crested combers existed throughout the exposed portion of the stream. These waves, moving up the current, soon were reduced below critical steepness by dissipation of energy in breaking and proceeded as a series of lower stable waves. The breaking phenomenon was due to the effect of reduction of the wave length by the opposing current and the resultant increase of steepness to the limits of stability. Off the entrance of the Columbia River the writer has observed five-sec waves breaking in 20 fathoms when meeting an ebb current of about two knots. The shoaling of five-sec waves would shorten the wave length less than one part in ten thousand, but the current would reduce the wave length by one part in thirteen. A wave originally at or near critical steepness would break when its wave length was reduced to this extent.

The proportionate reduction of wave length by opposing currents is greater for waves of short period than for waves of long period. Swell, usually considerably below a condition of critical steepness, is not greatly affected when an opposing current is first encountered. Some preliminary steepening occurs and the swell, if originally low, may become visible for the first time when it emerges from the choppy water at the seaward terminus of the tidal stream. The obscuring effect of the short choppy waves has been greatly reduced by their partial elimination in the breaking region. The swell, if sufficiently high, or wind waves, if of moderately long period and sufficient height, will proceed up the tidal stream, and will produce difficult or impassable conditions at some point farther shoreward. This apparently is due to the current distribution across the channel. In the case of the usual channel, ebb currents are stronger in the middle and weaker near the boundaries or at the shoals. Thus, the wave is retarded at the middle more than it is near the boundaries. Considering this effect alone for the moment, the usual ebb current is tantamount to a submarine ridge and will cause convergence of the waves into the middle of the channel. If the channel is flat in section or shallower in the middle than near the boundaries, or if the depths are sufficiently great that the waves are in deep water, this condition will prevail. If, however, the channel is essentially U- or V-shaped in section and the depths are shallow for the wave lengths involved, there will be an opposing effect tending to make the waves diverge. The dominance of the one or the other condition will depend upon the current distribution, slopes,

and similar factors. Most frequently, however, the swell converges in mid-channel and produces difficult conditions during an ebb. On the Columbia River, the swell may travel upstream to the channel off Desdemona Sands and break in a depth of water as great as or greater than that in which it has traveled over its entire path since entering the estuary.

In the winter of 1939 the writer observed breakers of approximately 13-sec period off No. 12 buoy in 70 ft of water, whereas the swell farther to sea was about 15 ft in height and well below critical steepness. Breaking crests converging at an angle to one another could be observed occasionally in the critical region, although only one dominant train of waves was noted farther to sea. An ebb current of two to four knots existed at the time. Following the turn of the tide and with a flood current of approximately one-half to one knot this breaking region moderated, although the wave height to seaward remained approximately constant. The writer has observed similar phenomena on other occasions on the Columbia and other entrances where no explanation was possible on the basis of refraction due to shoaling.

The two effects described above are apparent in Figure 6 of the paper by Johnson, where the short-period waves are seen to break at the entrance to Humboldt Bay soon after their entrance into the tide stream, whereas the longer-period swell breaks farther upstream. Bottom topography contributes to convergence in this particular case.

In partial confirmation of views expressed by Johnson is the phenomenon of ground swell entering bays or estuaries where it ordinarily does not enter for a brief period approximately at the time of slack water for both high and low stand. This is well known by fishermen and has been observed many times by the writer. The swell actually is the ocean swell passing through the entrance for a brief time and entering the upper bay or estuary during the period of slack current. There is no possibility that it is a bore phenomenon as no change in mean stage accompanies the swell nor is there a start of flood or ebb at the time. Sometimes only five or six crests occur but occasionally they will continue to enter for 15 or 20 min. This occurs most conspicuously at bays with narrow entrances. The writer has observed it most markedly at Nehalem Bay, Winchester Bay, and Rogue River, Oregon. Bays with extremely wide entrances admit a certain amount of ground swell during all stages of the flood, but it reaches regions not normally subjected near slack tide. Net fishermen look forward to this brief period of ground swell as they feel that it disturbes the salmon and causes them to move about.

It is apparent from these observations that the swell is profoundly affected by currents in either direction at the entrance, and can pass through a narrow entrance only at times when some very small current exists. Since divergence apparently exists in entrance channels during flood the lowering of waves is assisted by shoaling refraction in a U- or V-shaped channel section. In a flat channel section this is not the case. During the ebb, convergence apparently occurs and the resulting increase in wave height is somewhat alleviated by a U- or V-shaped channel section. In a flat bottom channel ideal conditions exist to produce high waves during the ebb.

Another marked effect of currents on waves is the moderating effect of current discontinuities in open water, as discussed by Johnson and illustrated by the accompanying photograph (see Fig. 1). The writer has been impressed strongly by this moderating effect on many occasions. He first encountered it at about 125°14′ W, 45°27′ N, off the Oregon coast in August 1939. A strong wind of 25 to 30 knots velocity had blown for 14 hours from the northwest. Waves of ten to 12 ft in height and about six-sec period existed. The sea was choppy and a course of 90° was being maintained. At sunset an extremely choppy and confused region was encountered and shortly thereafter the sea moderated greatly. A swell about four ft in height and 12 to 15 sec period and a light chop characterized the sea surface in this region. The writer was somewhat surprised by the sudden moderation, and although the wind had not decreased, the course was altered and the craft was headed back to carry out the intended work of the trip. Considerable flotsam was passed and almost immediately a choppy and confused sea was encountered. The craft was hove to on a sea anchor to leeward of the flotsam. The sea was moderate throughout the night. In the morning the wind had decreased to about 20 knots. The course was set westward and the flotsam line was encountered after an hour's run. An abrupt change in the color of the water could be noted at the debris line. The water to the seaward was extremely clear and blue, whereas that to the shoreward was slightly turbid and possessed a green appearance. The water to seaward apparently was flowing south relative to the green water at a velocity estimated at two knots and eddies were apparent where masses of floating seaweed rotated. To the seaward of this current junction the sea was extremely rough and choppy and tossing waves were apparent, similar to those encountered off precipitous headlands. Very smooth water existed to the shoreward. A fix was taken and the Fathometer showed no bottom to 100 fathoms. The writer cruised along this debris line for several hours. It followed a circuitous course with loops and bights departing three or four

mi from the general course of NNW. Several large dead fish (the oceanic sunfish, Mola Mola) were noted and several large mats of woven grass, glass floats, and wood heavily fouled with barnacles were observed. Heavy debris was by no means continuous and did not, in itself, constitute a barrier to the wind waves.

This same phenomenon was observed during subsequent trips in the same region. Several times it was observed as close as 30 mi to shore and occasionally as far as 250 mi. In approximately 75 trips during summers and falls of 1939 to 1941 it was observed as distinctly as above in perhaps 30 cases, less distinctly and with less continuity in about 35 cases, and occasionally no distinct transition and no moderation was found. Dead or dying oceanic sunfish were observed in almost every case of a distinct line. When hove-to to seaward of this region the craft's set to the south was made at one to three knots more than was experienced when hove-to to shoreward

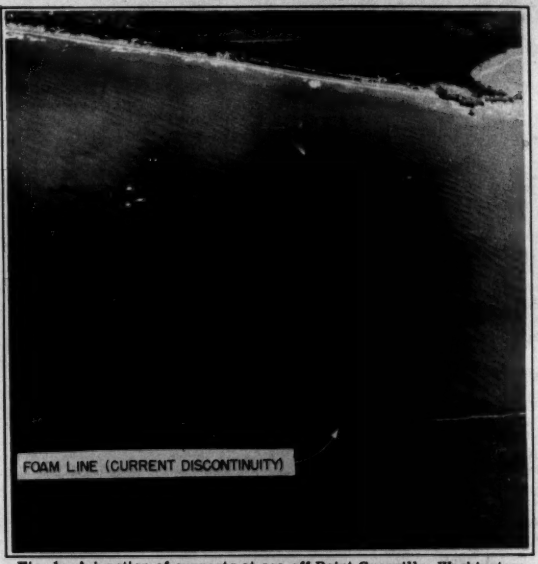

Fig. 1--A junction of currents at sea off Point Grenville, Washington; note that the short choppy waves in the foreground do not pass through the junction and only the longer waves pass through; thus, in this case, operation of small craft is smoother to the leeward of the current

under similar wind conditions. It was noted that many fishermen would operate in the "blue water" for albacore tuna, but would run shoreward during fresh weather and heave-to in the green water. The existence of this phenomenon was common knowledge among fishermen and was discussed frequently. The moderated zone existed for only a limited distance to leeward of the "rip," and when a craft left this region and ran shoreward the sea was found to increase in height and steepness. The relative velocities between the two currents seemed to be related to the duration and velocity of the northwesterly winds. After several days of fresh or strong winds the velocity difference was high. During an extended calm or southerly weather the current difference was much reduced. During the fall of 1940, the writer encountered southwesterly winds of gale force while in this region. The debris line was nearby but the moderating effect was not apparent.

References

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U. S. COAST AND GEODETIC SURVEY, U. S. coast pilot, Pacific Coast, 6th ed., Washington, 1942.

I. W. Johnson (University of California, Berkeley, California, Author's closure)--It was gratifying to read the comments of Isaacs and to have had the benefit of extensive observations on this phenomenon to add to the record of a paper which otherwise is primarily a theoretical treatment. As pointed out by Isaacs many of the general results of refraction of waves by currents have been known to mariners; however, a scientific explanation of these results in terms of the theory of gravity waves has not been made previously to the knowledge of the writer. Since the beginning of the War when research on various aspects of wave motion received considerable stimulus because of the need for such information in planning amphibious operations, much data of practical importance to mariners and engineers have been assembled. It is hoped that such discussions as that of Isaacs will reach such individuals to permit them to plan their operations with intelligence.

DISCUSSION OF

"SNOW SURVEY VERSUS WINTER PRECIPITATION FOR FORECASTING RUNOFF OF THE TUOLUMNE RIVER, CALIFORNIA" by H. P. BOARDMAN

[Trans., v. 28, pp. 752-765, 1947]

Marvin Diamond (Bureau of Reclamation, Boulder City, Nevada)--The author has compared the relative accuracy of snow surveys and winter precipitation as applied to forecasting the spring and summer runoff of a typical river on the western slope of the Sierra Nevada.

This writer investigated whether use of the long precipitation record that is available would result in an improved relationship between precipitation and runoff. The hazard of using short periods of record to determine the correlation between two variables for forecasting purposes is generally known. STANLEY and KENNEDY [1947, p. 771] have shown how any number of ten-year periods within a 33-year period may vary in correlation coefficients depending upon the decade selected. The weakness of snow-survey records to forecast runoff is the shortness of the snow-survey record. The strength of the precipitation record is its length. Since the author's paper did not include any values of correlation coefficients and standard errors of the estimate, these figures are presented in this discussion for the relationships studied.

The author states: "Abnormal fall precipitation probably has some effect also on the next April-July runoff, though it is not as great in quantity." This writer investigated the relationship between December-March precipitation and April-July runoff and also October-March precipitation and April-July runoff for the years 1930-1944. Table 11 shows the difference in correlation coefficients and errors of the estimate. The results show that the fall precipitation has a definite effect on the April-July runoff.

Table 11--Correlation of precipitation and runoff of Tuolumne River at Hetch Hetchy, California for years 1930-1944

Variables	Correlation coefficient	Standard error of estimate
		1000 ac ft
October-March precipitation versus April-July runoff[a]	0.897 ± 0.05	± 107.5
December-March precipitation versus April-July runoff[a]	0.858 ± 0.07	± 124.9

[a]Precipitation was weighted precipitation in inches for same six stations used to compute Table 9, p. 764; runoff was at Hetch Hetchy gage from Table 5, p. 756.

The author states that the runoff listed in the last column of Table 3 were adjusted by considering fall and spring precipitation. This adjustment does not check well with the data given in Table 2. Table 12 lists the fall and spring precipitation indicating whether it was below normal "BN", normal "N", or above normal "AN."

It is seen that in six of the years (1933, 1934, 1935, 1936, 1937, and 1940) the adjustment was made in a direction opposite to the deviation of fall and spring precipitation from normal.

The above runoff adjustment was used in estimating the snow-survey normals. Quoting the author, "In determining the April 1 normal for any snow course the average water equivalent for all of the available years was related to the average percentage of normal runoff for those same years, using the adjusted percentages of Table 3." Since, as shown by Table 12 below, the adjusted percentages of the author's Table 3 were determined quite arbitrarily, this writer used only the raw data and did not work with percentages.

The snow-survey runoff relationship as computed by this writer from the author's data given in Tables 5 and 6 on page 765, for the Hetch Hetchy gage and La Grange gage are shown in Table 13.

Table 12--Fall and spring precipitation in terms of relationship to normal, and direction of runoff adjustment by author

Year	October-November	April	Runoff adjustment by author
1930	BN	N	increase
1931	AN	BN	increase
1932	AN	BN	none
1933	BN	BN	increase
1934	BN	BN	increase
1935	AN	AN	decrease
1936	BN	BN	none
1937	BN	BN	none
1938	BN	AN	decrease
1939	AN	BN	increase
1940	BN	BN	increase
1941	BN	AN	decrease
1942	BN	AN	decrease
1943	AN	BN	none
1944	BN	AN	none

The author eliminated four years in determining the charts on pp. 758-759 on the basis that those years were abnormal. This writer does not believe that it is safe to eliminate data that do not appear to conform to the rest of the data. If the auhor is to eliminate these four years from the determination of his curves, how will he forecast similar years in the future? That is, what assurance will an operator using the forecast have that future runoff will not be similarly abnormal and differ widely from the forecast?

In eliminating 1932, it is said that it was preceded by four low years in succession. Table 14 gives the precipitation on the Tuolumne Basin and does not appear to bear out this contention. It is true that in three of the years October-March precipitation was below the average of five stations, but only one year appears even to approach exceedingly dry conditions.

Table 13--Correlation of water equivalents of snow runoff and of Tuolumne River for years 1930-1944

Comparison		Correlation coefficient	Standard error of estimate
			1000 ac ft
April 1 snow survey in inches of water	versus April-July runoff at Hetch Hetchy in 1000 ac ft	0.956 ± 0.03	± 71.3
April 1 snow survey in inches of water	versus April-July runoff at La Grange in 1000 ac ft	0.949 ± 0.03	± 167.4

Table 14--Average precipitation over Tuolumne Basin

Water year	October-November precipitation[a] (pct of normal)	October-March precipitation[a] (pct of normal)
1928	178	105
1929	80	70
1930	3	84
1931	117	62

[a]Average precipitation at West Point, Sonora, Twin Lakes, Hetch Hetchy, and Lake Eleanor.

This writer also computed the correlation coefficient between the April 1 "Water in snow," and the April-July runoff at Hetch Hetchy for the 15 years from 1930-1944 and for the 11 years eliminating 1932, 1935, 1937, and 1942. The correlation coefficient for the 15 years was 0.956 and for the 11 years 0.990.

In determining the precipitation-runoff relationship, the author used the December-March period of precipitation. This writer has shown earlier that the October-March period has a better correlation with the April-July runoff. A longer period of precipitation records is available than was used. The fact that only 15 years of snow-survey records are available is no reason to confine the precipitation record used for comparison to that same period when 30 years of record are available. An operator is interested in utilizing the best method based on all available material. This writer made a number of correlations which are summarized in Table 15. Note that slightly better results are obtained when the three precipitation

stations within the basin are used by themselves than when they are combined with three stations outside of the basin as used by the author.

Fig. 15--Correlation of precipitation and runoff of Tuolumne River

Correlation		Correlation coefficient	Standard error of estimate
Of	With		
			1000 ac ft
April-July runoff at Hetch Hetchy	October-March precipitation[a] 30 years, 1915-1944	0.863 ± 0.05	± 104.1
April-July runoff at Hetch Hetchy	October-March precipitation[a] 15 years, 1930-1944	0.905 ± 0.05	± 103.4
April-July runoff at Hetch Hetchy	October-March precipitation[b] 15 years, 1930-1944	0.865 ± 0.07	± 124.0
April-July runoff at La Grange	October-March precipitation[a] 30 years, 1915-1944	0.821 ± 0.06	± 268.5
April-July runoff at La Grange	October-March precipitation[b] 30 years, 1915-1944	0.797 ± 0.07	± 284.0

[a]Average precipitation at Lake Eleanor, Hetch Hetchy, and Sonora.
[b]Average precipitation at Lake Eleanor, Hetch Hetchy, Sonora, Tamarack, West Point, and Twin Lakes.

Comparing Tables 15 with Table 13 shows that snow surveys give a smaller error of the estimate than does precipitation in forecasting the April-July runoff of the Tuolumne river at Hetch Hetchy and La Grange, California. There is no assurance, however, that this will still be true after 30 years of snow record have been accumulated. The fact that the relationship between precipitation and runoff did not change appreciably by using 30 years instead of 15 years, as indicated in Table 15, is also no assurance that the same will apply to the snow record. This writer would like to emphasize again that when two forecasting methods are compared it is not necessary to confine one method to a short period of record simply because the other method has a short record. In developing forecasting methods all data available should be used. Also data should be adjusted only by methods wherein chance for personal bias is eliminated.

References

STANLEY, J. W., and KENNEDY, R. E., Forecasting Colorado River flow, Trans. Amer. Geophys. Union, v. 28, pp. 766-779, 1947.

Charles D. Hopkins, Jr. (U. S. Weather Bureau, Portland 9, Oregon)--The author's procedure for forecasting spring runoff in the Tuolumne Basin from snow survey data is an excellent example of the "normal" method. Other methods, however, take better advantage of the nature of precipitation observations.

A number of precipitation stations in the general area of the Tuolumne Basin have records that began prior to 1925. If the full period of precipitation record were to be used in developing a forecasting relation for the Tuolumne, the stability of the relation would be considerably enhanced. Furthermore, a long record makes possible the use of multiple correlation methods, the advantages of which are pointed out later.

The stability of a relation is as important as its ostensible accuracy. In this connection, it is of interest to quote STANLEY and KENNEDY [1947] regarding the practice of the United States Bureau of Reclamation on forecasting inflow into Lake Mead, "The forecasts based on precipitation records are considered reliable, while those based on the 1936-1945 snow data record should be used with caution because the ten-year period is too short to furnish a reliable indication of runoff to be expected under all the varying conditions that may occur. Relationships between snow data and runoff for the available period of record are included below, however, along with those between precipitation and runoff for the longer period, 1913-1945. Conclusions drawn from the snow data relationships are considered as tentative only because additional years of measurements could cause considerable change in the relationships." While the contrast between precipitation and snow-survey data is not as marked in the Tuolumne, the conclusion that there is an advantage in having a longer record is valid.

In developing precipitation-runoff forecasting relations, a term including last year's precipitation may be introduced to represent the carry-over effect. A forecast can be made as of any given date by adding to a partial precipitation index computed from observed precipitation, an amount corresponding to the median subsequent precipitation of record. In addition, by the use of the quartiles and the extremes of record, forecasts can be made with some knowledge of the possible effects of future meteorological events on the runoff.

Weighting of snow survey data by means of the elevations of the snow courses and the area-elevation curve of a basin is at best an arbitrary procedure. The assumption is made that the amount of snow residual from precipitation is largely a function of elevation. But this seems a drastic simplification of the result of a very complex process. SPREEN [1947] has shown that in mountainous country there are several topographic variables affecting average seasonal precipitation such as elevation, orientation and exposure angle, and slope. While this work applies to average precipitation, annual data are closely related to these topographic parameters. Measurements made on snow courses yield the residuals of precipitation minus melt, evaporation, and sublimation. Melt and evaporation and sublimation in mountainous country cannot be said to be functions solely of elevation. The complexity of the problem seems too great to be overcome by any direct, inductive process of reasoning.

Although precipitation or snow observed at a given location can be used as an index of precipitation or snow over nearby areas, the relative importance of a given snow course or precipitation station in mountainous country cannot be assigned by any inductive logic. One practical method of assigning weights of significance to such observations is multiple correlation. The question as to just how many cases are necessary in any multiple correlation with a given number of variables depends to some extent on the results of that correlation. To use this technique, it is necessary to use fairly long records, the longer the better. The advantages of multiple correlation techniques are manifold. In addition to being a practical method of assigning station weights, it can be used to assign weights to each month's precipitation and to assign a weight to that of the previous year. If due regard is paid to the limitations of statistical methods, multiple correlation is an extremely powerful tool.

References

SPREEN, WILLIAM C., A determination of the effect of topography upon precipitation, Trans. Amer. Geophys. Union, v. 28, pp. 285-290, 1947.

STANLEY, J. W., and KENNEDY, R. E., Forecasting Colorado River flow, Trans. Amer. Geophys. Union, v. 28, pp. 766-779, 1947.

Walter T. Wilson (U. S. Weather Bureau, San Francisco, California)--This discussion has two parts. In the first part, Boardman's paper is regarded as a specific challenge which hardly can be ignored in view of his striking conclusion. The second part deals with a few relevant aspects of the more general problem of forecasting seasonal volume of stream flow.

Figure 5 presents the relationship between seasonal stream flow of the Tuolumne River at Hetch Hetchy and antecedent precipitation at Lake Eleanor. The stream flow is expressed in per cent of normal for April through July for each of the 15 years studied by Boardman, and the values are taken from his Table 8. These values differ slightly from those on record at the Hetch Hetchy office in San Francisco, but the differences do not particularly favor any of the methods displayed. Further, the corrections for evaporation are also small, and need not enter this discussion. The precipitation values for Lake Eleanor are accumulated precipitation for the period December through March for each of the corresponding years. Lake Eleanor is one of the stations Boardman used in his demonstration.

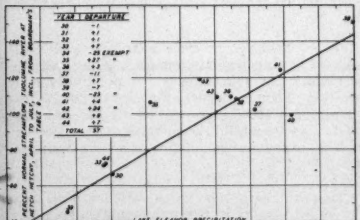

Fig. 5--Relationship between stream flow and antecedent precipitation

The line in Figure 5 is not a least squares line, and could be improved, but it will serve its purpose. Following the procedure established in this paper the departures of the 11 best points are totaled, making 57 in all. This total departure is considerably less than that which

Boardman used as a measure of the quality of precipitation data in comparison with snow surveys. While this total departure of 57 is not as good as either of the totals for the two snow survey methods, respectively, 38 and 26, it represents a mean error of about five per cent in the basin which had been selected for Boardman's comparison, and is a first approximation based on a single station. It may be observed that the four years exempted from comparison in this simple relationship are not the same as those which Boardman omitted from his snow-survey totals. This fact should cause no concern. It seems only fair, in comparing two different kinds of data, that each should be entitled to its most favorable interpretation. Any system will do better some years than others, and the fact that the poor years are not identical merely indicates that different relationships are expressed.

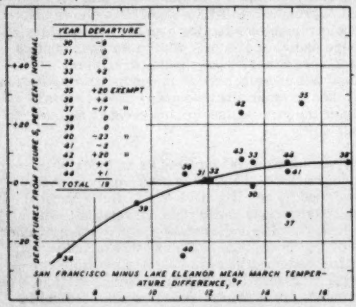

Fig. 6--Relation between departures from curve on Figure 5 and a third variable

As an example of an additional type of relationship between stream flow and antecedent precipitation, Figure 6 shows the departures from the line of Figure 5, plotted against corresponding values of a third variable. This third variable is entirely objective, being the difference in mean March temperatures between San Francisco and Lake Eleanor. Assuming again the privilege of excluding the four worst years, the total of the departures of the remaining 11 points is now 19, which represents a mean error of less than two per cent, and is superior to that of each of the snow-survey methods. Lest some unsympathetic critic suggest that San Francisco temperatures are irrelevant, two things may be said. The first involves the somewhat delicate defense that if the author is permitted to adjust his values without describing an objective process, a discusser is entitled to the use of an esoteric variable. The second is this: The basin chosen for comparison has scanty precipitation data, and it has been necessary to employ an indirect method of indicating the distribution of snow at the end of March each year. This indirect method may be described by example. In 1938 the snow pack covered the basin so generally and was so deep that bare ground did not appear at Lake Eleanor until April 28. The air, passing over this great expanse of snow, cooled considerably in its regular west to east movement. The mean March temperature difference between San Francisco (to the west) and Lake Eleanor in 1938 was nearly 17° F. In contrast, the winter of 1934 was characterized by a spotty snow cover, and the mean temperature difference that year was less than 7° F. This small temperature difference may have indicated but little cooling of the air as it passed over what little snow was on the ground that month.

A different, but no less plausible, explanation of this temperature gradient function is that during a wet March, having little sunshine, the air is cooled much on its way from the coast to a mountain station, but in a dry March, such as 1934, the air would be cooled less. This function may thus not only provide a measure of general precipitation (or extent of snow cover), as contrasted with the observations possible at a single station, but gives special weight to precipitation occurring at an important time of year.

In his discussion of the four years which he excluded from verification, Boardman indicated fall precipitation as one of the factors disturbing the snow-survey relationship. It is suggested that instead of ignoring such a variable, an attempt might be made to interpret it quantitatively, and thus use it in improving the estimate of stream flow. Figure 7 shows, for each of the 15 years, the departure in Boardman's snow-survey relationship for Hetch Hetchy against his corresponding per cent of normal fall precipitation. It is questionable whether fall precipitation is an important additional factor in this relationship, or whether it is an expedient explanation of a poor estimate in isolated cases.

Referring again to adjustments to "normal," which begs definition, unless the data required for this adjustment are presented to the reader, one might suspect that this information for a particular season might not always be available or apparent at the time the stream flow is to be estimated. Further, if this adjustment merely shows a better correlation with past records, the relationship may not be improved. It is the location and shape of the regression line which determines the quality of estimates based on it.

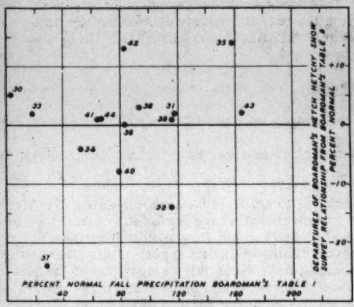

Fig. 7--Relationship between values shown in Boardman's paper

Undoubtedly, as Boardman may show in his closing discussion, the snow-survey relationship for this basin period may be improved. It may be pointed out that the exclusion of four years helped one method more than the other. It appears that no general conclusion regarding the relative merits of different types of data or of different methods of analysis can be justified on the basis of this one example. It also seems clear, and it is to be emphasized, that this example does show what can be done with a short record.

With respect to the more general problem of forecasting stream flow, Boardman has assigned weights to snow courses according to the size of the elevation zone each represents. In addition to the area-elevation function which he has described, consideration might also be given to other parameters which influence the distribution of precipitation. Among these parameters are slope, orientation, degree of exposure [SPREEN, 1947], position along a slope, concavity or convexity of a site, and height and distance of obstructions. Except for elevation, latitude, and longitude, each of these parameters may be measured differently (and perhaps operates differently) according to the size of area over which it is considered, For example, the local aspect of a sampling point may be different from the large scale aspect of the mountainside on which it is situated.

In sampling precipitation over a mountainous basin, it is not enough to distribute the sample areally and to sample the range of elevation. A fundamental principle of sampling is the necessity of sampling all the characteristics which influence the distribution of precipitation. The areal distribution is related to storm paths. To the extent that storms may be widespread and that the seasonal accumulation of paths does not favor any particular path, areal sampling may be less important than sampling the other parameters. And these other parameters may sometimes be sampled in adjoining basins, or even farther away.

The sampling of snow cover is complicated by the introduction of elements causing depletion in addition to those influencing accumulation. Besides sampling the deposit of successive storms as they pass over a rugged range, snow surveys are influenced by evaporation, melting, blowing, and other changes. And these may be taking place in one part of the basin at the same time accumulation is occurring elsewhere. Further, the very nature of a snow course restricts its use. It has been the practice to lay out snow courses where the snow "lies well," that is, where the effects of blowing, for example, are minimized. This eliminates the sampling of the windswept components of drainage basins. Similarly on side hills and near waterways, snow courses may be influenced by drainage from upslope.

Because of the obscure and subtle way in which these topographic and other parameters affect the relation between precipitation and stream flow, it may not be possible to isolate and assign appropriate quantitative influences to each factor. Instead of acquiring what is regarded as an understanding of the physical processes, it may be necessary to rely on statistical relationships among the various so-called causes and effects. A pragmatic solution is to let the basin integrate its own equation. Instead of arbitrarily assigning weights to apply to each observation (on the basis of elevation, proportion of area, or any other prejudgment) use of a multiple regression analysis provides the proper weights inherent in the available data. To be emphasized here is the fact that with the large number of variables operating, it is desirable to use as many years of record and choose from as many stations as possible. Otherwise, a fortuitous combination of too few data may result in a high but misleading correlation.

A conclusion such as Boardman's is necessarily based on a comparison which is difficult to make without academic restrictions. From the standpoint of producing a reliable result, there is no reason to omit any of the relevant available data. The precipitation record goes back many years. How any 15-year portion of the period of record compares with the total is a matter of luck.

Compared with the regression for the entire period of record, the regression based on one 15-year portion may be steep and the regression based on another portion may be flat, or even translated. To show the location and shape of the regression based on the entire record for the

Tuolumne would require a comprehensive study. This study would more appropriately be the subject of an original paper than a discussion having the purpose merely of showing the limitations of a restricted method of handing a short record. STANLEY and KENNEDY [1947] have shown rather convincingly the superiority of a long record.

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H. P. Boardman (Nevada Cooperation Snow Surveys, Reno, Nevada. Author's closure)--With regard to the discussion by Diamond, it is natural to expect that a long period for comparison of two such related series of observations as precipitation and stream flow should disclose a more dependable relationship than a short period. However, Diamond did not appear to discover any advantage of 30 years over 15 years for this particular case. For a fair comparison of the two methods I am still of the opinion that the same period of years should be used for both. As a matter of fact for the Truckeee River and Lake Tahoe basins of the eastern slope of the Sierras we have a sufficient number of snow courses surveyed for more than 25 years, to establish relationships, and several courses have been surveyed for from 30 to 38 years.

In Diamond's first reference to "abnormal factors" he quotes a sentence from my paper relating to abnormal fall precipitation and might well have also quoted the preceding sentence relating to abnormal spring or runoff-season precipitation which has a more direct and greater effect on the runoff though it comes after the April 1 forecast. Diamond shows a better correlation and lower standard error of estimate for October-March than for December-March precipitation related to April-July runoff. This should be expected and the way most of us snow-survey forecasters take care of that is to modify or adjust the runoff estimate lindicated by snow surveys alone by raising or lowering it in accordance with very high or very low October-November precipitation.

There is some reason for Diamond's criticism of my arbitrary adjustment of runoff percentages in the last column of Table 3. However, if in Table 12 he had shown the percentages as given in Table 2 instead of merely giving AN for above normal and BN for below normal, it would not look so bad. On a rexamination of Tables 2 and 3, if I had it to do over, I would make a few changes of several per cents but the only one I would change in direction would be for 1944 where I would drop the value to about 68 per cent instead of raising it to 75 per cent as I did before. These changes would probably have little effect on the determination of snow-survey normals, for which purpose the adjustments were made.

Diamond criticises the omission of four abnormal years and says "if the author is to eliminate these four years from the determination of his curve, how will he forecast similar years in the future?" The graphical relationship I was attempting to determine is between weighted snow-survey results and actual runoff for approximately normal conditions other than snow-water equivalent. This relationship is to be used as a guide but not blindly followed as something mathematically accurate.

I have already commented on adjustment for abnormally high or low fall precipitation. As to abnormal spring precipitation, if the forecast is based on conditions only up to April 1, unless one can correctly foretell precipitation for one or two months ahead one can not expect results to check with the forecast closely if the spring precipitation is very high or very low.

If 100 years of record were available perhaps the high and low abnormal years would balance up so that their inclusion would be justified but if they are to be included where only a few years are available then the position of these "spots" on the graph should be changed, this adjustment involving evaluation of the abnormal factor or factors.

Diamond takes exception to my explanation of why the runoff of 1932 fell short of what should have been expected. I had in mind conditions on the eastern slope and particularly the runoff and did not check sufficiently on the precipitation records. It is true as he shows that the October-March precipitation was above normal for 1928, but special attention is called to the runoff values for April-July in percent of normal shown in Table 16.

Table 16--Per cent of normal runoff, April-July, 1928-1931

Year	Tuolumne River at La Grange	Eastern slope basins		
		Truckee River	Rise of Tahoe Apr. 1 to Max.	West Walker River
1928	65	62	66	62
1929	61	44	47	52
1930	62	65	65	64
1931	31	24	33	31

Table 17--Fall and winter precipitation at Lake Eleanor, 1927-1928

Period	Precipitation	
1927	in	pct of normal
Oct.-Nov.	10.77	181
Dec.	6.39	95
1928		
Jan.	3.13	38
Feb.	3.81	47
Mar.	14.15	239
Oct. 1927-Mar. 1928	38.25	110

The apparently great discrepancy between the 1928 precipitation and runoff is well illustrated by comparing the above table with the precipitation records for Lake Eleanor (see Table 17).

Nearly all of the heavy March precipitation occurred near the end of the month, 12.2 inches of the total fell March 22 to 27, inclusive. This was rain except in high altitudes, causing considerable floods in many streams. The peak discharge of this flood in the Truckee River of the eastern slope was approximately 85 per cent of the maximum flood rate recorded since records started in 1900.

Since most of this heavy precipitation had run off before April 1, the April-July runoff was much lower than should have been expected from October-March precipitation totals.

However this flood storm must have contributed generously to low altitude ground-water levels so probably I should not have included 1928 in my series of low years preceding 1932.

Giving the precipitation method the advantage of using the October-March period and the 30-year length of record Diamond finds the values shown in Table 18 for the standard error of estimate in 1000 ac ft units. This shows a decided advantage in accuracy for snow surveys over winter precipitation for forecasting runoff.

Table 18--Comparison of Diamond's estimates of standard error

Method	Place of gaging	
	Hetch Hetchy	La Grange
By snow survey	71.3	167.4
By precipitation	104.1	265.2
Ratio P/S	146 pct	158 pct

The above standard errors of estimate must have been based on including all 15 years. I have computed the standard error for the Hetch Hetchy runoff using the data from Table 5 and the formulas from Figure 1 and the results for all 15 years are: 66.1 for the weighted snow-survey water equivalent and 64.1 for the weighted per cents of normal. For 11 years, omitting the four abnormal years the values are 27.1 and 23.0, respectively, all errors of estimate being in 1000-ac ft units.

Omitting the abnormal years these standard errors of estimate are less than four per cent of the normal runoff of the Tuolumne River at Hetch Hetchy.

With regard to the discussion by Hopkins, again I wish to acknowledge the advantage of long time records in developing relationships for forecasting stream flow.

However, as time goes on the snow-survey method is gradually acquiring longer records and I believe that where a fair comparison is made the advantage will usually be found with the snow-survey method as was the case in the Tuolumne basin. Of course the ten years of snow surveys available in the Colorado basin is rather short and what little work I did on that basin several years ago seemed to indicate that all of the tributaries did not act in parallel for all the years.

Of course topography, character of soil and other factors have a marked effect and extreme accuracy should not be expected. The Sierras and especially the eastern slope, where practical

snow surveys-stream flow forecasting was first developed by J. E. Church, is perhaps as near an ideal region for this method as can be found, because so large a proportion of the annual water supply nearly always comes from the snow fall in the mountains. Certainly the carry-over effect of the previous year's precipitation should not be omitted from consideration and in some basins ground-water observations in wells and soil moisture tests can help measure this effect.

As to weighting according to altitude zones and areas, that seems to be a more reasonable attack than to take a simple average of all snow courses. In the Truckee and Tahoe basins of the eastern slope we use only two such zones, high level and low level. The water equivalent in the upper zone snow courses is in nearly all cases much greater than for the lower courses and therefore deserves more weight for forecasting than the water equivalent of the low courses. In general, 7000 ft altitude is the dividing elevation but there are exceptions in the cases of some snow courses because of their behavior. It would seem foolish to attempt to formulate a general rule to be followed in forecasting for all basins. Each region should be in some respects a problem by itself.

Hopkins speaks of "multiple correlations." Whether or not the following is what he had in mind, I wish to state that since writing the paper on forecasting the Tuolumne River flow and for the last year or so I have been developing a graphical relationship between the water equivalent for each snow course which has a sufficiently long record, and the seasonal runoff at the regular gaging station. From these graphs and the resulting relationship formulas I make separate forecasts of the runoff for each year and by weighting these separate forecasts I get a general forecast for each year. Then by plotting these forecasts against the actual runoffs for the various years I get a general graph for the basin. This is for the Truckee and Tahoe Basins of the eastern slope.

This method of forecasting along with the forecasts based on weighting of water equivalents and of percentages of normal gives three results, which should not differ very greatly. A discussion of these relationships for the Sierra Eastern Slope Basins will probably be published before long as a bulletin of the Nevada Agricultural Experiment Station, University of Nevada, Reno, Nevada.

With regard to the discussion by Wilson, let me first state with regard to the slight differences in the figures of the flow of Tuolumne River between the San Francisco records and those I used, that my values were furnished me by the California Cooperative Snow Surveys.

Figure 6, showing the relationship between the departures from his graph line in Figure 5 and the difference in March temperature between San Francisco and Lake Eleanor, is interesting. However, if his explanation about the wide difference in temperature variation between the years 1934 and 1938 is of particular significance why is it that the years 1931 and 1932 so nearly coincide on his graph when 1931 was an extremely low year, even lower than 1934, although 1932 was a fairly heavy year in snow blanket. I think there is a good field for research in studying the relationship between departure from normal spring temperature, especially for the month of May, and probable loss or gain in total April-July runoff as compared with what snow-survey forecast indicates.

Referring to Wilson's discussion of Figure 7, the graph of this Figure does not take into account disturbing factors other than abnormal fall precipitation, in particular abnormal spring precipitation which has a much greater effect. This illustrates the difficulty of taking into account graphically, the effect of two or more disturbing factors which may act in the same direction or in opposite directions. I am still of the opinion that at least until a long-time record is available, the rejection of abnormal years from the determination of the regression line is entirely justifiable and that if they are to be included they should be adjusted by evaluating the effect of the abnormal factor or factors. Such evaluation of abnormal spring precipitation for instance, if considered quantitatively may involve the application of an assumed abnormal precipitation, plus or minus, to an area, all or a certain portion of the basin. Or the effect may be estimated by considering the relation of the abnormal precipitation to the normal precipitation for the same period and also searching past history for similar years.

I want to emphasize that the purpose of snow surveying in this western country is not to determine quantitatively the amount of water equivalent in the snow blanket on a watershed but to determine how much will run off. What is more it works and has worked successfully within reasonable limits for a considerable number of years.

One of the principal reasons for the superiority of snow surveying over measurement of precipitation by the United States Weather Bureau gages is that each snow course consists of several sampling points and the average of these different measurements is used whereas the United States Weather Bureau catch can of whatever type catches the precipitation at only one location.

Research conducted under my direction and presented in a paper by HUNTER and DEVORE [1937], shows the relation for different years between the measured water equivalent of each sample and the average water equivalent for the whole course. For example, a certain sample number may range between 60 per cent and 130 per cent of the course average over a period of ten or 15 years. In fact in some of the poorer courses the range for some samples was as much as between 20 per cent and 200 per cent. A wide range might indicate drifting along the course but the drifts shifting in position for different years. Where the extreme range between maximum and minimum per cent of the mean for most of the samples is not more than 40 per cent to 60 per cent that is a very well located course.

It is easy to see that unless a United States Weather Bureau rain gage is well located its precipitation catch may not be truly representative of that region every year. Of course if storms are not widespread, different snow courses or different United States Weather Bureaus precipitation stations will not receive proportional catches. However, most of the heavy winter storms in the Sierra Nevada seem to be quite general judging by the measured results.

Another point in favor of the snow-survey method is that the measurements on which the forecast is largely based are taken at about the end of the snowfall season and show the residue remaining which will supply most of the runoff for the forecast period.

Whether winter precipitation or snow-survey method is used for forecasting, the total indeterminate absorption losses will probably be different in different basins and certainly different for different years in any one basin, temperature being perhaps the factor having the greatest effect in causing variation in absorption losses. On the eastern slope it is quite usual for the water equivalent on "low level" snow courses to be less on April 1 than on March 1 due to early melting.

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NOTES AND PERSONALIA

NOTES

Corrigenda--The following corrections are noted in the Transactions:

Vol. 29, June 1948, p. 367, in paper by R. W. Gerdel, equation (1). The portion at the right of the solidus should read "area of plate in cm^2."

Vol. 29, June 1948, p. 372, in paper by R. W. Gerdel on Figure 1. The equation for k should be as shown by equation (3) on page 371 instead of as given on Figure 1.

Vol. 29, August 1948, p. 496, in paper by V. J. Schaefer, Figure 4 was inadvertently printed upside down.

Vol. 29, August 1948, p. 606, note regarding the death of François E. Matthes. He received his baccalaureate degree from Massachusetts Institute of Technology in 1895, not 1896 as stated.

Norwegian Polar Institute--On March 1, 1948, the Norges Svalbard-og Ishavs-Undersøkelser was replaced by the Norsk Polarinstitutt under the direction of H. U. Sverdrup. The publications will be continued without break in numbering as the Norsk Polarinstitutt Skrifter and Norsk Polarinstitutt Meddeleser.

New in-service organ of the United States Coast and Geodetic Survey--The first issue of The Journal, in-service organ of the United States Coast and Geodetic Survey, has recently been distributed. While this is not available on subscription or for general distribution, it contains much of interest to geodesists, oceanographers, seismologists, and others, and reprints of most of the papers may be secured through the Survey office, Washington 25, D. C.

Centennial Celebration of the American Association for the Advancement of Science--The Centennial Celebration of the AAAS was held in Washington, D. C., September 13-17, 1948. About 3000 scientists from all over the country attended. Many leading scientists from the many fields of science were among the speakers.

Norwegian-Swedish-British Antarctic expedition--Plans are being formulated for a Norwegian-flag Antarctic Expedition, which will be partly supported by Sweden and Britain, and under the direction of the Norwegian Polar Institute. Meteorological, glaciological, topographical, and geological investigations will be conducted. Present plans call for sending aircraft and personnel to Queen Maud Land by whaleship in the season 1949/50, and leaving a wintering party until 1951-1952.

New circular describing maps of Alaska--The United States Geological Survey has prepared a leaflet entitled Maps of Alaska to provide up-to-date information on maps available. This circular may be secured without charge by writing to the office of the Survey, Washington 25, D. C.

Meetings of the American Meteorological Society--The Ninety-Ninth Meeting of the American Meteorological Society was held at the University of California, Berkeley, California, June 23-24, 1948. The One-Hundredth Meeting was held September 10-11, 1948 at Franklin Institute, Philadelphia, Pennsylvania.

Japanese oceanographic vessels--No. 1 Tenkai Maru was engaged in making current observations at Hirato in July 1948, while No. 4 and No. 5 Kaiyo Maru conducted oceanographic surveys in the East China Sea, and to the eastward of Honshu, respectively.

Third Annual Meeting of Rocky Mountain Hydraulic Laboratory--The Third Annual Meeting of the Rocky Mountain Hydraulic Laboratory was held at Allenspark, Colorado, August 21, 1948. A scientific and a business session were held.

Return of Atlantis--The research vessel Atlantis of Woods Hole Oceanographic Institution returned to Woods Hole in June via Bermuda from her trip to the Mediterranean.

New Arctic weather stations--New meteorological observation stations have been established on Isachsen Island and Prince Patrick Island in the Canadian Arctic.

C. O. Clark is now in Caracas, Venezuela, as consulting engineer to the Ministry of Public Works on hydraulic and hydrologic problems in connection with building several systems of irrigation and in developing a staff of Venezuelan engineers for such work.

Ashton R. Codd has recently been appointed to take charge of the snow-survey work of the Division of Irrigation of the Soil Conservation Service in the Upper Missouri and Upper Columbia River valleys with headquarters in Bozeman, Montana.

Glen N. Cox has been appointed Professor of Hydraulics and Mechanics at New York University. Until recently he was Director of the School of Hydraulic Engineering at Louisiana State University.

Jno. A. Fleming, Honorary President of the American Geophysical Union, has been elected an Honorary Fellow of the Geophysical Observatory, University of Alaska in recognition of his long and outstanding work in terrestrial magnetism and allied fields of the Earth Sciences, and for his furtherance of international scientific relations.

I. Ross Heverly, formerly of the Division of Meteorology and Department of Physics, Pennsylvania State College, is now Assistant Professor of Physics at the United States Naval Academy.

Mark Wallon Jones has been appointed a member of the staff of the Geophysical Observatory University of Alaska.

Rufus J. Le Blanc, until recently Chief of the Geological Section of the Mississippi River Commission, has accepted a position as Senior Research Geologist with the Exploration and Production Research Division of the Shell Oil Company, with headquarters in Houston, Texas.

Paul F. Lee, Chief of Naval Research, retired from the United States Navy on July 1, 1948. He was succeeded by Thorvald A. Solberg.

Robert L. Pendleton of the Office of Foreign Agricultural Relations of the United States Department of Agriculture, and the Johns Hopkins University, has recently been appointed a Special Fellow for the study of tropical soils and land use practices in the Belgian Congo by the Belgian American Educational Foundation. He is now spending a four-month period on field studies.

Thos. C. Poulter, until recently Associate Director of the Armour Research Foundation, has resigned to become Associate Director of the Stanford Research Institute, and is currently working on a new development in seismic exploration that eliminates the necessity for drilling shot holes.

C. Warren Thornthwaite has been appointed Professor of Climatology at Johns Hopkins University, and Director of its new Field Laboratory of Climatology located at Seabrook, New Jersey.

Gerald A. Waring has recently retired from the United States Geological Survey after 42 years of professional work and has taken up residence in Palo Alto, California.

Warren S. Wooster of Scripps Institution of Oceanography is accompanying the Navy 1948 Point Barrow Resupply Expedition as oceanographer aboard the icebreaker Burton Island.

Walter Youngquist has recently received his Ph. D. degree in geology from the University of Iowa and has been appointed Assistant Professor of Geology in the School of Mines at the University of Idaho.

Jonathan B. Brown, Extension Specialist in Irrigation, University of California, died on January 7, 1948 after a protracted illness. He was born in Greenville, Illinois on March 12, 1887 and received his baccalaureate degree in Civil Engineering from the University of California in 1912. He engaged in hydrographic work for the California Reclamation Board and other organizations until 1917, then served overseas in the First World War. From 1919 until 1945 he was engaged on hydraulic and hydrologic work with the California Department of Engineering and entered on his duties with the University in 1945. He had been a member of AGU since 1935.

H. G. Fourcade of Cape Town, South Africa, died January 19, 1948.

UNION, SECTION, AND COMMITTEE ACTIVITIES

INFORMAL REPORT ON THE EIGHTH GENERAL ASSEMBLY OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS HELD IN OSLO, NORWAY, AUGUST 19 TO 28, 1948

The Eighth General Assembly of the International Union of Geodesy and Geophysics opened on August 19, 1948, at the University of Oslo as scheduled. Its first general meeting was attended by His Majesty King Haakon VII and Crown Prince Olav. Halvor Solberg, President of the Norwegian National Committee made an address of welcome. This was followed by addresses by Norwegian Foreign Secretary Halvard M. Lange and Vice-Chairman Brynjulf Bull of the City Council. Response was made by Acting President of the Union N. E. Nørlund of Denmark. Following this was the first plenary assembly of the Union at which the delegates and guests were advised of the action of the Executive Committee and the Council of the Union at their meetings during the first two days preceding the formal opening of the General Assembly.

The scientific sessions of the various Associations started in the afternoon of August 19 and the presidential addresses followed in succession before the seven Associations during August 19-21. The scientific sessions in the various Associations included papers and reports that brought forth the outstanding developments in the various countries since the Seventh General Assembly in 1939. In Geodesy this included a review of loran, shoran, improvements in triangulation and leveling, and progress in gravimetric surveys and the development of simpler gravimeters. In Seismology considerable time was devoted to seismic survey work and techniques as well as to natural seismic occurrences. A joint assembly was held by Seismology, Meteorology, and Oceanography on microseisms---their theory, measurement, and interpretation. In Meteorology, improved techniques for the measurement of dew or frost point, the study of thunderstorms, developments in synoptic and long-range forecasting, the optics of the atmosphere, and variations in climate received attention. A joint session was held with the Association of Terrestrial Magnetism and Electricity on the physics of the upper atmosphere. In Terrestrial Magnetism and Electricity the various wartime developments such as the airborne magnetometer as well as extensive work undertaken at the various magnetic observatories, including ionospheric studies and magnetic surveys, were discussed. A session was devoted to the effects of solar activity on terrestrial phenomena. In Oceanography the extensive studies of ocean swell, turbulence, tides, and currents that have taken place throughout the world were reviewed. In Vulcanology much time was devoted to the catalogue of volcanoes, extinct and active, and interesting papers were given on various volcanic activities throughout the world. In Hydrology, the Commissions presented programs which in part ran concurrently with the regular meetings of the Association. A review of developments that have taken place in the various countries since 1939 relating to runoff, snow and ice, subterranean waters, and lakes was given.

In addition, a session was held by the Commission on Continental and Oceanic Structure in which some general interesting papers were presented relating to the Earth's crust. Two general evening sessions were held, both open to the public. One was an address by Merle A. Tuve entitled "Geophysics--Vocation or Avocation" and the other, a lecture on the eruption of Mt. Hekla, Iceland, in 1947 and early 1948 by Sigurdur Thorarinsson; the lecture was accompanied by a spectacular motion picture in color.

Thirty-nine nations were represented at the meetings and there were nearly 500 delegates and guests in attendance. Those countries represented were as follows: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, Chile, China, Czechoslovakia, Denmark, Ecuador, Egypt, Finland, France, Great Britain, Greece, Hungary, Iceland, India, Indo-China, Israel (a representative present, not seated as a delegate because of non-recognition of Israel), Italy, Mexico, Monaco, Morocco, The Netherlands, New Zealand, Norway, Peru, Philippine Republic, Poland, Portugal, Siam, South Africa, Spain, Sweden, Switzerland, Turkey, and the United States of America. It was understood that the USSR sent representatives to Oslo, but they refused to be seated as delegates in accordance with direction of their Government because of the presence of delegates from Spain.

Sixty-seven delegates and guests in attendance from the United States were as follows: Leason H. Adams; K. Hilding Beij, Mrs. Beij, and Pierce Beij; Merrill Bernard; J. A. B. Bjerknes and Mrs. Bjerknes; Robert C. Bundgaard; Charles R. Burrows; Horace R. Byers, Mrs. Byers, Miss Byers, Mrs. Krick, and Miss Krick; James E. Church; Charles J. Clifford; Robert S. Dietz; E. G. Droessler;

Richard M. Field; Richard H. Fleming; Ralph E. Gibson; John A. Goff; Beno Gutenberg and Mrs. Gutenberg; Henry W. Hemple; Jørgen Holmboe and Mrs. Holmboe; Floyd W. Hough; Edward O. Hulburt; Norman Hagen; J. Wallace Joyce; Joseph Kaplan; John A. Ladd; Walter D. Lambert; Helmut Landsberg; Gunnar Leifson; Walter C. Lowermilk and Miss Lowdermilk; James B. Macelwane; John W. MacMillan; C. D. Meany; Walter H. Munk and Mrs. Munk; G. W. Musgrave and Mrs. Musgrave; Charles S. Piggot; F. W. Reichelderfer; Roger R. Revelle, Mrs. Revelle, and two daughters; L. H. Rumbaugh; Walter E. A. Ruska; R. Dana Russell and Mrs. Russell; A. Nelson Sayre, Mrs. Sayre, and Miss Sayre; Waldo E. Smith; A. F. Spilhaus; Edward B. Stephenson; Harald U. Sverdrup and Mrs. Sverdrup; M. A. Tuve and Mrs. Tuve; Fred L. Whipple; and Charles A. Whitten.

The final plenary session was held on August 28. Brussels, Belgium, was selected as the meeting place for the Ninth General Assembly to be held in 1951. The officers of the Union elected were: President, F. A. Vening Meinesz (The Netherlands); Vice-Presidents, Sidney Chapman (Great Britain), and L. H. Adams (U. S. A.). James M. Stagg continues as General Secretary. The Committee on Finance consists of J. Tuzo Wilson (Canada), Chairman; K. Hilding Beij (U. S. A.), Secretary; A. T. Doodson (Great Britain); Gerardo Dianderas (Peru); and Jean Vignal (France).

Resolutions of the Associations and of thanks to various individuals and groups contributing to the success of the Assembly were accepted. Allocation of dues paid by member nations for the years 1948-1950 was made as follows: Association of Geodesy, 43 per cent; Association of Seismology, nine per cent; Association of Meteorology, nine per cent; Association of Terrestrial Magnetism and Electricity, 12 per cent; Association of Oceanography, nine per cent; Association of Vulcanology, six per cent; Association of Hydrology, nine per cent; and Office of the International Union, three per cent. The unit of subscription for 1949-1951 remains unchanged, namely, £100 per unit of membership. It was recommended that Mexico and Australia each be requested to increase membership status from one unit to three units, and that member nations that have not paid their dues since the close of the War should for the present be considered members, but that they be reminded of their obligations to IUGG.

Officers of the Associations are as follows:

Geodesy--President, Walter D. Lambert (U. S. A.); First Vice-President, C. F. Baeschlin (Switzerland); Second Vice-President, A. Letroye (Belgium); Secretary, P. Tardi (France). Section of Triangulation--President, P. Jacquinet (France); Secretary, J. M. Tienstra (The Netherlands). Section of Leveling--President, G. A. Rune (Sweden); Secretary, Jean Vignal (France). Section of Astronomy--President, N. E. Nørlund (Denmark); Secretary, B. C. Browne (Great Britain). Section of Geoid--President, J. de Graaf-Hunter (Great Britain); Secretary, Guy Bomford (Great Britain). C. A. Whitten (U. S. A.) was appointed Rapporteur for the subject of projections under the Section of Triangulation. H. W. Hemple (U. S. A.) was appointed representative of the IUGG on the commission of experts considering cartographic matters for the United Nations.

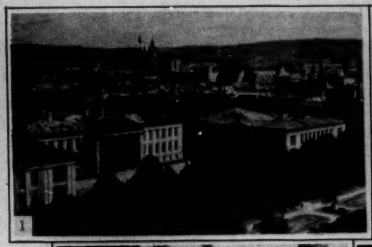
Seismology--President, R. Stoneley (Great Britain); Vice-Presidents, Frank Neumann (U. S. A.) and Ch. Charlier (Belgium); Secretary, Jean-Pierre Rothé (France). Executive Committee--Markus Båth (Sweden); Pietro Caloi (Italy); Alois Zátopek (Czechoslovakia); and Ernest Wanner (Switzerland). Commission of the International Seismological Summary--President, Harold Jeffreys; Members--Beno Gutenberg; E. A. Hodgson; L. Lehmann; James B. Macelwane; Eijo Vesanen; and the President (Stoneley) and Secretary (Rothé) of the Association.

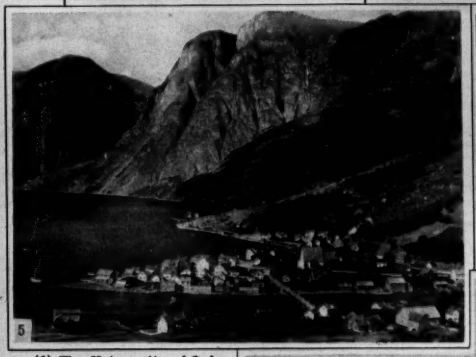
Meteorology--President, J. A. B. Bjerknes (U. S. A.); Vice-Presidents, K. R. Ramanathan (India) and F. W. Reichelderfer (U. S. A.); Secretary, Jacques van Mieghem (Belgium). Executive Committee--Walter Mörikofer (Switzerland); Charles Normand (Great Britain); and Viho Väisälä (Finland).

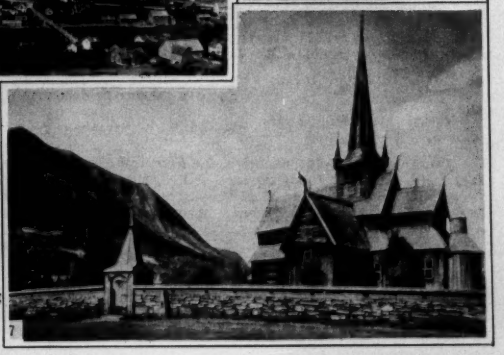
Terrestrial Magnetism and Electricity--President, S. Chapman (Great Britain); Vice-Presidents, J. Coulomb (France) and B. F. J. Schonland (South Africa); Secretary, J. W. Joyce (U. S. A.). Executive Committee--Olaf Lützow-Holm (Argentina); S. K. Banerji (India); L. V. Berkner (U. S. A.); v. Laursen (Denmark); D. F. Martyn (Australia); and the last past President (Jno. A. Fleming, U. S. A.).

Oceanography--President, H. U. Sverdrup (U. S. A.); Vice-Presidents, J. Proudman (Great Britain) and C. O'D. Iselin (U. S. A.); Secretary, H. Mosby (Norway); Deputy Secretary, R. H. Fleming (U. S. A.). Executive Committee--J. N. Carruthers (Great Britain); H. Pettersen (Sweden); J. Rouch (France); and J. W. Termijtelen (The Netherlands).

Vulcanology--President, B. G. Escher (The Netherlands); Vice-Presidents, Howel Williams (U. S. A.), L. Glangeaud (France), Dr. MacGregor (Great Britain), and Niels Nielsen (Denmark); Secretary, F. Signore (Italy).







(1) The University of Oslo; (2) W. D. Lambert, Adelbert Prey (Austria), N. E. Nørlund, and F. A. Vening Meinesz; (3) W. Schermerhorn (The Netherlands); F. A. Vening Meinesz, and W. Heiskanen (Finland); (4) J. Tuzo Wilson, K. Hilding Beij, and J. M. Stagg; (5) Aurland on Aurlandsfjord, branch of Sognefjord, a scenic high point on one excursion; (6) P. A. Grinaker, Secretary, Norwegian Organizing Committee, and Miss Grinaker; (7) Stave church at Lom with Mt. Lom (6800 ft) in the background

Hydrology--President, Merrill Bernard (U. S. A.); First Vice-President, V. Frolow (France); Second Vice-President, Giulio de Marchi (Italy); Secretary, Léon Tison (Belgium). Commission of Surface Waters--President, Jan Smetana (Czechoslovakia). Commission on Subterranean Waters--President, A. Nelson Sayre (U. S. A.); Secretary, V. Frolow (France). Commission on Snow and Ice (formerly Snow and Glaciers)--President, H. W. Ahlmann (Sweden); Secretary, P. D. Baird (Canada). Temporary Committee on Land Erosion--President, Walter C. Lowdermilk (U. S. A.).

The Commission on Continental and Oceanic Structure was dissolved, and a new Joint Com- on the Physics of the Earth's Interior was established with Beno Gutenberg as its Convener; two representatives are to be designated by each interested Association and members of the old Commission who desire to be members of the new Committee will be co-opted.

With several Association meetings under way simultaneously in many instances, delegates found themselves extremely busy in attempting to attend those in which they had particular interest. Formal and informal evening gatherings were numerous. Among the functions attended by the American delegates were receptions by the Norwegian National Committee, the American Embassy, and the City of Oslo. On Sunday (August 22) there was an excursion to Lillehammer, an interesting city four hours by train to the north of Oslo. From Lillehammer station a trip by bus was made into the mountains above the timberline, stopping at roadside hotels for dinner. Upon returning to Lillehammer the group was taken to Maihaugen, the site a most interesting ethnographic museum relating to that part of Norway, and was addressed at a reception by the Mayor of Lillehammer; Acting President Nørlund responded most appropriately.

Following the General Assembly, which was officially closed at about noon on August 28, there were several excursions to the scenic heartland of Norway, its rugged mountains with their glacier-filled high valleys, and the beautiful fjord country of western Norway. Many of the delegates and their guests took part in these excursions and enjoyed the further fellowship of their colleagues from various lands. Harmony and the unity of science, seemed to be the unexpressed keynotes of this important gathering. The carefully planned arrangements of the Norwegian Organizing Committee and the beautiful settings of Oslo were great contributing factors to the success of the Eighth General Assembly.

WALDO E. SMITH

Inter-American Conference on Conservation of Renewable Natural Resources--An Inter-American Conference on Conservation of Renewable Natural Resources was held in Denver, Colorado, September 7 to 20, 1948 under the auspices of the Pan American Union. The American Geophysical Union was invited by the Department of State to become a member of an Advisory Group. This invitation was accepted and Stanley W. Lohman was designated as representative from the American Geophysical Union.

American Standards Association--The Committee on Photography Z38 is reviewing the need for Standard Z52.61-1945 titled Photographic Filter Terminology and Nomenclature. Any member who has any statement to make regarding the need for, and benefits derived from, such a standard, should correspond at once with your representative on Committee Z38; Fred Anderegg, Department of Geology, Princeton, New Jersey.

Special Announcement

Thirtieth Annual Meeting of AGU

The Thirtieth Annual Meeting of the American Geophysical Union will be held in Washington, D. C., with dates tentatively set for April 20, 21, and 22, 1949. Confirmation is to be made by the Executive Committee soon. A more definite and complete announcement will be made in the December issue of the Transactions. Keep these dates free on your calendar, and make plans to come.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 29 DECEMBER 1948 Number 6

INVERSE COMPUTATION FOR LONG LINES

P. D. Thomas

Abstract--Using the series development of the elliptic integral expressing the length of the elliptic arc between two points on an ellipsoid lying in the plane determined by the two given points and the center of the ellipsoid, together with formulas for the azimuths of the normal sections determined by the two given points, an inverse position form is developed which gives a good approximation to the true geodesic length and geodesic azimuths.

A problem of importance in geodesy is the task of obtaining the azimuths at each end of a line connecting two points and the distance between them when the latitude and longitude of each of the two points are given, the Earth being considered an oblate spheroid.

The general problem has been solved, and formulas can be found in several places, for instance, in Die mathematischen und physikalischen Theorieen der höheren Geodäsie by F. R. Helmert or in Handbuch der Vermessungskunde by W. Jordan, both of whom rely on the earlier work of Bessel. Inspection will reveal that the chief difficulty with the rigorous method of Helmert or Jordan, which yields the geodesic distance and geodesic azimuths, is that it requires an iteration or reworking process for long lines. If one insists on the best accuracy in obtaining the geodesic distance between two points, and the geodesic azimuths are required, then one must have recourse to the iterative methods. This is necessary since in the inverse problem the latitude of the vertex of the geodesic through the two points is not known, nor can it be found except by successive approximations. However a high degree of accuracy can be obtained by approximating the geodesic distance with the elliptic arc lying in the plane of the two points and the center of the ellipsoid (the great elliptic arc), and by using the azimuths of the two normal sections of the ellipsoid determined by the two given points. (The two normal sections are the two planes determined by the normals at the two given points with the given points. These two planes coincide when both points are in the same latitude. They both coincide with the meridian when both points are in the same longitude.) Since the vertex of this arc can be found directly, the iteration process is avoided. The purpose of this paper is to develop an inverse position computation form based on the great elliptic arc approximation.

In Volume 50, number 7, 1943 of the American Mathematical Monthly, L. E. Ward in an excellent paper shows that the difference in length of this great elliptic arc and the geodesic length is of the fourth order in the eccentricity, and that on a line about 8000 mi in length, this difference is about 30 ft. In his problem he was not concerned with azimuths, but he derived in connection with his proofs certain formulas which will be used here in somewhat modified form.

Ward obtains the following expression for the parametric latitude of the vertex of the great elliptic arc

$$\sin \theta_0 = \sqrt{\frac{\tan^2 \theta_1 - 2 \tan \theta_1 \tan \theta_2 \cos \Delta\lambda + \tan^2 \theta_2}{\tan^2 \theta_1 - 2 \tan \theta_1 \tan \theta_2 \cos \Delta\lambda + \tan^2 \theta_2 + \sin^2 \theta \Delta\lambda}} \quad \ldots\ldots\ldots (1)$$

where θ_1 and θ_2 are the parametric latitudes of the two given points and $\Delta\lambda$ is the difference of their longitudes.

In the following expression for the length of the great elliptic arc between two given points, Ward's form has been modified by use of obvious trigonometric identities and by inclusion of the fourth order terms in the eccentricity.

$$s = a \left\{ d_1 + d_2 - (e^2 \sin^2 \theta_0)[d_1 + d_2 - \sin (d_1 + d_2) \cos (d_1 - d_2)]/4 - (e^4 \sin^4 \theta_0)[6(d_1+d_2) - 8 \sin (d_1 + d_2) \cos (d_1 - d_2) + \sin 2 (d_1 + d_2) \cos 2 (d_1 - d_2)]/128 \right\} \ldots\ldots (2)$$

where $\cos d_1 = \sin \theta_1 / \sin \theta_0$, $\cos d_2 = \sin \theta_2 / \sin \theta_0$.

One may obtain by elementary methods, or find on page 330 of Helmert's höheren Geodäsie, the following formulas for the azimuths of the normal sections determined by the two points.

$$\left.\begin{aligned}\cot \alpha_1 &= \frac{(\cos \Delta\lambda \sin \theta_1 - \tan \theta_2 \cos \theta_1) + e^2 (\sin \theta_2 - \sin \theta_1) \cos \theta_1 \sec \theta_2}{\sqrt{1 - e^2 \cos^2 \theta_1}\, \sin \Delta\lambda} \\ \cot \alpha_2 &= -\frac{(\cos \Delta\lambda \sin \theta_2 - \tan \theta_1 \cos \theta_2) + e^2 (\sin \theta_1 - \sin \theta_2) \cos \theta_2 \sec \theta_1}{\sqrt{1 - e^2 \cos^2 \theta_2}\, \sin \Delta\lambda}\end{aligned}\right\} \quad \ldots (3)$$

In these azimuth formulas, P_2 (θ_2, λ_2) is considered to be west of P_1 (θ_1, λ_1) and azimuths are reckoned clockwise from south, following the convention used in the United States.

From (1), (2), and (3) we have the essential elements to construct an inverse position computation form. There is needed additionally, however, the constants of the ellipsoid of reference to be used, the formula for converting geodetic latitudes to parametric form, and a sign convention for the quantities entering (1), (2), and (3) to allow the two given points to be located anywhere on the surface of the ellipsoid with respect to latitude and longitude.

The ellipsoid of reference chosen upon which to base the form is the Clarke 1866, since all the triangulation on the American Continent is based on it. The square of its eccentricity is $e^2 = 6.7686580 + 10^{-3}$, and its equatorial radius is a = 6,378,206.4 m.

The formula for converting geodetic latitude, ϕ, to parametric latitude, θ, is $\tan \theta = (1 - e^2) \tan \phi$, and for the Clarke spheroid this becomes

$$\tan \theta = 0.996609925 \tan \phi \quad \ldots (4)$$

Equation (4) is easily derived, since it is merely the relation between the angle ϕ, which the normal to an ellipse at a given point makes with the major axis, and the eccentric angle θ of the given point.

For the sign convention it is to be noted from (3) that when the signs of cot α_1 and cot α_2 are opposite, the vertex is between the two given points and both d_1 and d_2 in (2) are considered positive. When cot α_1 and cot α_2 have like signs, the vertex is external to the two points, and the numerically larger, d_1 or d_2, is considered positive; the smaller is negative. If P_2 is chosen to the west of P_1 so that the difference in longitude, $\Delta\lambda = \lambda_2 - \lambda_1$, is always positive, then α_1 is in the first or second quadrant and α_2 is in the third or fourth quadrant according as the signs of cot α_1 and cot α_2 are positive or negative. d_1 and d_2 are in the first or second quadrants according as cos d_1 and cos d_2, as given by the expressions under (2), are positive or negative. $d_1 + d_2 \leq \pi$, since we are interested in the shorter of the two elliptic arcs connecting the two given points. Hence, whenever $d_1 + d_2 > \pi$, the sum is to be subtracted from 2π to obtain the correct value. By this device we may consider the radical giving sin θ_0 in (1) always positive.

The form will be prepared for machine computation requiring eight place tables of the natural trigonometric functions. Since the signs of the quantities d_1 and d_2 in (2) depend on the signs of the azimuths, according to the sign convention established above, the form must allow computation of the azimuths first.

Equation (1) is written in the form

$$\sin \theta_0 = \sqrt{K/(K + 1)} \quad \ldots (5)$$

where

$$K = (A \tan \theta_1 + B \tan \theta_2)/ \sin^2 \Delta\lambda \quad \ldots (6)$$

$$A = \tan \theta_1 - \tan \theta_2 \cos \Delta\lambda \qquad B = \tan \theta_2 - \tan \theta_1 \cos \Delta\lambda \quad \ldots (7)$$

Equations (3) may be written

$$\cot \alpha_1 = U_1 (R_1 - B) \qquad \cot \alpha_2 = U_2 (A - R_2) \quad \ldots (8)$$

where $U_1 = \cos \theta_1 / T_1 \sin \Delta\lambda$ $\qquad U_2 = \cos \theta_2 / T_2 \sin \Delta\lambda$

Table 1--Form for inverse position computation (Clarke 1866 spheroid),

$e^2 = 6.7686580 \times 10^{-3}$

a = 6,378,206.4 m

1 radian = 206,264.8062 sec

ϕ_1	+49° 50′ 59.800″	1.	NAPLES	λ_1	-14° 14′ 55.500″
ϕ_2	+21° 18′ 06.000″	2.	HONOLULU	λ_2	+157° 49′ 18.000″
$\tan \phi_1$	+0.864694663	$\tan \phi_2$	+0.390917722	$\Delta\lambda = (\lambda_2 - \lambda_1)$	+172° 04′ 13.500″

$\tan \theta = 0.996609925 \tan \phi$

$\tan \theta_1$	+0.865176524	$\tan \theta_2$	+0.38959198	$T_1 = \sqrt{1 - e^2 \cos^2 \theta_1}$	+0.99805604
$\sin \theta_1$	+0.652807652	$\sin \theta_2$	+0.36301526	$T_2 = \sqrt{1 - e^2 \cos^2 \theta_2}$	+0.99705733
$\cos \theta_1$	+0.75752373	$\cos \theta_2$	+0.93178319	$\sin \Delta\lambda$	+0.13796595
$\cos^2 \theta_1$	+0.57384220	$\cos^2 \theta_2$	+0.86821991	$\cos \Delta\lambda$	-0.99043836

$A = (\tan \theta_1 - \tan \theta_2 \cos \Delta\lambda)$	+1.24763208	$B = (\tan \theta_2 - \tan \theta_1 \cos \Delta\lambda)$	+1.24311733
$K = (A \tan \theta_1 + B \tan \theta_2)/\sin^2\Delta\lambda$	+81.9402733	$C = e^2 (\sin \theta_2 \cdot \sin \theta_1)$	-1.96150054 x10^{-3}
$R_1 = C/\cos \theta_2$	-2.10510923 x10^{-3}	$R_2 = -C/\cos \theta_1$	+2.58936495 x10^{-3}
$U_1 = (\cos \theta_1/T_1 \sin \Delta\lambda)$	+8.50175030	$U_2 = (\cos \theta_2/T_2 \sin \Delta\lambda)$	+8.7741419
$\cot \alpha_1 = U_1 (R_1 - B)$	-6.85090293	$\cot \alpha_2 = U_2 (A - R_2)$	+8.43409642

$\alpha_F = \alpha_1$ 171° 41′ 43.451″ $\alpha_B = \alpha_2$ 186° 45′ 42.421″

From NAPLES to HONOLULU

$\sin \theta_0 = \sqrt{K/(K+1)}$	+0.99395328	$\sin^2 \theta_0$	+0.98794313	$\sin^4 \theta_0$	+0.97603163
$N = 1.6921645 \times 10^{-3} \sin^2 \theta_0$	+1.6717623 x10^{-3}			$P = 3.5793 \times 10^{-7} \sin^4 \theta_0$	+3.4935 x10^{-7}
$\cos d_1 = \sin \theta_1/\sin \theta_0$	+0.65677898			$\cos d_2 = \sin \theta_2/\sin \theta_0$	+0.36522366
d_1	+48° 56′ 43.153″	$H_r = (d_1 + d_2)$	+2.0511803 (rad)	V = (1 - N - 6P)	+0.99832614
d_2	+68° 34′ 43.149″	L = sin H cos Q	+0.83525988	W = (N + 8P)	+1.6745837 x10^{-3}
$H = (d_1 + d_2)$	+117° 31′ 26.302″	M = sin 2H cos 2Q	-0.63456592	P	+3.4935 x10^{-7}
$Q = (d_1 - d_2)$	-19° 37′ 59.996″	cos Q	+0.94186215	cos2Q	+0.77420858
sin H	+0.88681755	sin 2H	-0.81963173	$s = a(H_r V + LW - MP) = a\Sigma$	13,069,875.0 m

H_r V	+2.04774691		
LW	+0.00139869		
(- MP)	+0.00000022		
Σ	+2.04914582		

Note: Station 2 is always west of station 1. α_1 is in the first or second quadrant according as the sign of cot α_1 is plus or minus. α_2 is in the third or fourth quadrant according as the sign of cot α_2 is plus or minus. d_1 and d_2 are in the first or second quandrants according as the signs of cos d_1 and cos d_2 are plus or minus. When cot α_1 and cot α_2 have opposite signs, the signs of d_1 and d_2 are both plus. When cot α_1 and cot α_2 have like signs, the numerically larger of d_1 or d_2 is considered plus; the smaller is minus. When $d_1 + d_2$ is greater than 180, subtract from 360.

$$T_1 = \sqrt{1 - e^2 \cos^2 \theta_1} \qquad T_2 = \sqrt{1 - e^2 \cos^2 \theta_2}$$

$$R_1 = C/\cos \theta_2 \qquad R_2 = -C/\cos \theta_1$$

$$C = e^2 (\sin \theta_2 - \sin \theta_1)$$

It is seen that the quantities A and B given by (7) enter into the determination of the value of $\sin \theta_0$ as well as the azimuth determinations which is of advantage in preparing the form.

If in (2), $H = d_1 + d_2$, $N = e^2 \sin^2 \theta_0/4 = 1.6921645 \times 10^{-3} \sin^2 \theta_0$, $L = \sin (d_1 + d_2) \cos (d_1 - d_2)$, $P = e^4 \sin^4 \theta_0/128 = 3.5792759 \times 10^{-7} \sin^4 \theta_0$, $M = \sin 2 (d_1 + d_2) \cos 2 (d_1 - d_2)$, then (2) may be written

$$s = a (HV + LW - PM) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

where

$$V = (1 - N - 6P) \qquad W = N + 8P$$

Table 1 shows the elements arranged from (4), (5), (6), (7), (8), and (9) in a sequential manner for machine computing. Note that the inverse computation shown between Naples and Honolulu gives a distance of about 8100 mi. The error, as compared with the geodesic distance obtained by more rigorous methods, is of the same order as obtained by Ward. The azimuths differ from the geodesic azimuths by approximately three min.

If another ellipsoid of reference were to be used, say the International, the only necessary changes to be made in the form would be in the numerical values of e^2 and a, and the numerical factors in (4) and P and N of (9).

For two points nearly antipodal, larger errors in azimuth and distance can be expected, since the separation of the vertices of the great elliptic arc and the geodesic arc would be much greater, the vertex of the geodesic being much closer to the corresponding pole of the Earth.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

(Communicated manuscript received May 3, 1948;
open for formal discussion until May 1, 1949.)

Transactions, American Geophysical Union Volume 29, Number 6 December 1948

LEVEL DIVERGENCES, SEISMIC ACTIVITY, AND RESERVOIR LOADING IN THE LAKE MEAD AREA, NEVADA AND ARIZONA

D. S. Carder and J. B. Small

In an earlier report [CARDER, 1945], maps showing the epicenters of nearly 500 small local shocks in the Lake Mead area, Nevada and Arizona, were published. They showed a concentration of these epicenters along the south border of the basin occupied by the lower lobe of the lake. It was concluded that many of these local earthquakes were caused by a downfaulting of the crustal block occupied by this arm of the Lake against the granitic masses to the southeast and southwest. It was mentioned that this downsettlement was probably a renewal, on a small scale, of pre-Pleistocene activity under the stimulus of a suddenly added load of 12 billion tons of water. Supporting evidence for this conclusion is the subject of the present paper.

In 1935 the United States Coast and Geodetic Survey, with the aid of Bureau of Reclamation funds, established a net of first-order levels in the area at a time when the reservoir behind the Hoover Dam had begun to fill. The levels were rerun in 1940-1941, also with the aid of Bureau of Reclamation funds, during the period of highest water when the reservoir was filled to near capacity. Therefore, the two levelings showed a condition of near minimum and near maximum reservoir load.

In the load peak for 1936, when about one-third of the reservoir capacity had been reached, numerous small earthquakes were reported by local residents. It was not definitely known whether or not these small shocks were common in the area because in pre-construction days the region was uninhabited, and during construction small shocks may have been associated with blasting operations and therefore overlooked.

It was mentioned in the earlier papers [MEAD and CARDER, 1941; and CARDER, 1945] that three accelerographs purchased by the Bureau of Reclamation were installed in 1937 at Boulder City, and early in 1938 a single component Wood-Anderson seismograph was also installed. In 1940-1941, other stations were added at Overton, Pierce Ferry, and Hoover Dam. Since that time, the epicenters referred to in the opening paragraph have been located.

In a report of the BUREAU OF RECLAMATION [1939], a map was published showing the calculated vertical displacements of the Lake Mead reservoir bed, on the basis that the crust is an unfaulted granite slab 18 mi thick floating on basaltic magma. This map, with slight modification, is reproduced as Figure 1.

Figure 2 is a composite map showing the actual settlement according to level operations, and the calculated position of epicenters of local earthquakes. Preparation of the divergence contours requires a large amount of interpolation between widely spaced level lines, but the map shows the general complexity of the situation and the apparent lack of correlation of seismicity and settlement of the reservoir.

The seismic situation in relation to reservoir settlement clears when the geology of the area is considered. An examination of the type of rock crossed by the level lines shows that areas of granite or pre-Cambrian gneisses and granites are relatively positive areas where little or no settlement occurs. This is irrespective of the distance from load centers. An apparent exception to this rule is on the plateau about ten mi south of Pierce Ferry where a granite outcrop appears in a negative area near the line of levels. Other crossings in known granitic areas show definite positive divergence trends.

Figure 3 is a map of the area covered by a selected part of the level net showing pertinent geology [LONGWELL, 1936] along the lines of levels. Stipled areas are of granitic rocks: Monzonites or pre-Cambrian granites and gneisses. Solid lines, not part of level lines or surface features are the larger known faults. Dotted lines, not part of washes, and others are indicated faults. Numerals on level lines are distances in miles. The complex structure in the Muddy Mountains is not indicated here because it has no direct bearing on the problem.

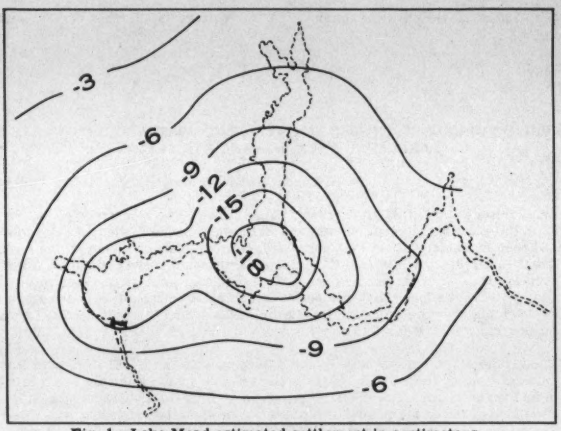


Fig. 1--Lake Mead estimated settlement in centimeters
(Courtesy of Bureau of Reclamation)

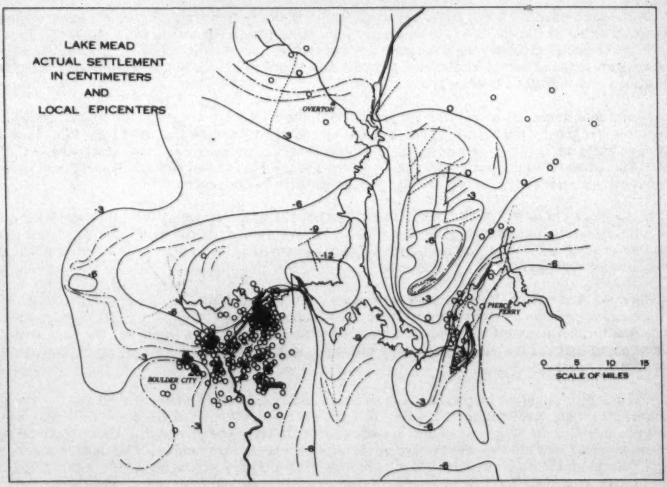


Fig. 2--Observed settlement from 1935 to 1941, and the local epicenters
(small circles) from 1941 to 1946

A profile of a selected part of the level net is shown in Figure 4. The profile begins at a point about ten mi northeast of Las Vegas. From there it goes generally eastward across Bonelli Bay and in the direction of the arrows of Figure 3 across Hoover Dam, through Las Vegas, Moapa, Overton, across an upper arm of the Lake, southward through Pierce Ferry, and back across the Lake at Gregg Basin, terminating as shown. Divergences appear beneath the corresponding level profile.

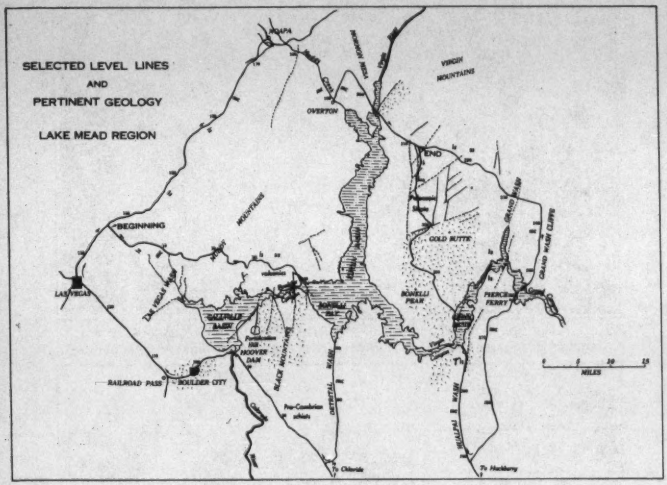


Fig. 3--Level lines selected; ls, Paleozoic limestone; ss, sandstone; mc, Muddy Creek formation, consisting of gypsiferous playa silt and terrace gravel; Tls, late Tertiary limestone, the upper member of the Muddy Creek formation

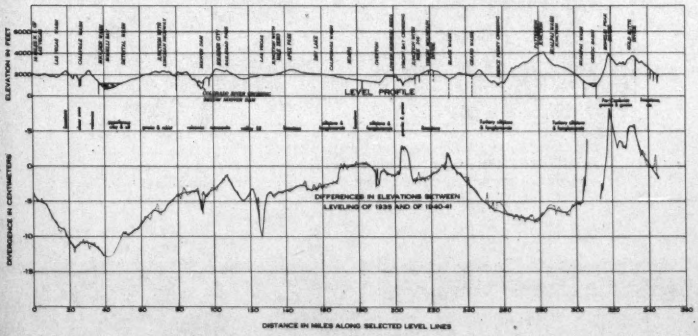

ELEVATION IN FEET
LEVEL PROFILE
DIVERGENCE IN CENTIMETERS
DIFFERENCES IN ELEVATIONS BETWEEN LEVELING OF 1939 AND OF 1940-41
DISTANCE IN MILES ALONG SELECTED LEVEL LINES

Fig. 4--Profile of level net; vertical lines in the upper figure are known or indicated faults; dotted lines in the lower figure connect observed divergences

At only two places do the divergences follow the level profile. These are at the Boulder-Detrital Wash crossing of the Lake at Bonelli Bay and in the mountain area across the Bonelli Peak and Gold Butte Divides. Elsewhere there is no definite correspondence. Noteworthy are the positive areas at the Gregg Basin crossing and at the Virgin Bay crossing. A granite spur from the Virgin Mountains is responsible for the narrows at the Virgin Bay crossing, and probably also for the positive divergence area at that place.

In 1940-1941, after the reservoir had filled, tide gages were used to extend the line of levels across the Lake at Gregg Basin and at the Boulder Wash-Detrital Wash crossing (see Figs. 5, 6,

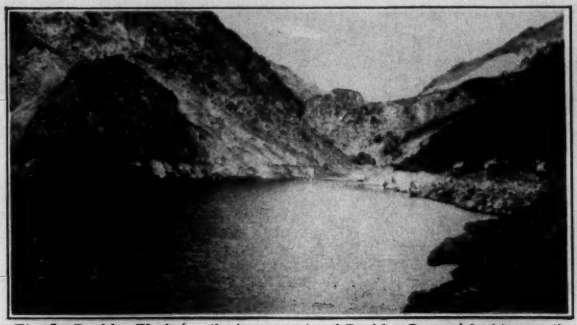


Fig. 5--Boulder Wash (north shore, east end Boulder Canyon) looking north showing tide-gage station; this is the area of greatest observed settlement

Fig. 6--Hualpai Wash looking southeast showing tide-gage station; line of levels in Wash at right center; Hualpai (late Tertiary) limestone at center and left center just above high-water mark; upper center, toward upper left corner, pre-Cambrian granite and gneiss

Fig. 7--Northwest shore of Gregg Basin looking west showing tide-gage station; pre-Cambrian granites and gneisses form mountain mass at center and right center; this is the area of greatest positive divergence

Fig. 8--View showing difficulty encountered in running some of the level lines

and (7). At least one major fault runs the length of Gregg Basin between the two bench marks nearest the north and south shores of the lake. According to the divergence profile, the south shore is moving upward in respect to the north shore. The underlying rock on the south shore is Late Tertiary Hualpai limestone, and on the north shore

it is pre-Cambrian gneiss which seems to negate the belief that areas underlain by sedimentary rocks are settling relative to areas of granite. However, the Hualpai limestone which forms the bedrock under the bench marks on the south shore overlaps a mass of pre-Cambrian granite which outcrops within a few hundred feet. When the line of levels approaches the south shore, a sudden upward trend in the divergence profile begins about a mile south of the lake. This roughly coincides with the near proximity of the granitic area.

The settlement near Las Vegas is probably caused by withdrawal of artisian water in the basin with a corresponding compaction of the sediments in and overlying the aquifer.

Ordinarily first-order leveling by the United States Coast and Geodetic Survey conforms to specifications of the Board of Survey and Maps which states that lines should be run in both a forward and backward direction with section checks within the criterion 4.0 mm. $\sqrt{K}$ (where K is the length of section in km). The leveling of 1935 in the vicinity of Hoover Dam and the releveling of 1940-1941 were run under the criterion 3.0 mm. $\sqrt{K}$ as it was realized that we would be attempting to measure small movements of bench marks and it was desired to do the most accurate leveling justifiable. The total length of the net of lines is about 700 mi. Some of the roads along which the original work was done were abandoned after Lake Mead was formed which made the releveling slow and more difficult (see Fig. 8).

Level divergences are a relative condition. A datum of zero was chosen at Cain Springs north of the area because of its distance from the reservoir. The over-all extremes in divergence are a matter of about eight inches which is relatively small considering the distances involved. Future levelings over the established lines will no doubt show more conclusively what is actually happening. Nevertheless, the information at hand shows definite trends and is believed to be sufficient to point to the conclusions drawn from this study. A sketch showing the divergence between the two levelings is available on request to the United States Coast and Geodetic Survey, Washington 25, D. C. for those interested in additional details of the leveling, but it is too detailed to reproduce here.

Acknowledgment--The authors thank the members of the staff of the Chief Engineer, Bureau of Reclamation, and of the Commissioner, Bureau of Reclamation who critically reviewed this article prior to publication.

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STUDIES OF DEEP CRUSTAL LAYERS BY EXPLOSIVE SHOTS

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Our broad objective in beginning this program was to try and learn more about the nature of the Earth's crust, such as the kind of compensation occurring under mountain regions, the geological nature of large gravity anomalies and the correlation of isostatic adjustment with crustal structure. The immediate objective began as a project to determine the layering of the crustal structure underlying the region around Washington, D. C., and the Appalachian Highlands.

The methods proposed were to use the best combination of refraction, vertical, and critical angle reflection of seismic waves resulting from controlled detonations of high explosives.

The program began as a cooperative venture between the Department of Terrestrial Magnetism and the Geophysical Laboratory of the Carnegie Institution of Washington, together with the active collaboration of various branches of the United States Navy. Other collaborators are the New Mexico School of Mines (E. J. Workman) and Columbia University (M. Ewing).

The first phase of the investigation was concerned with the development of suitable instrumentation and techniques. This is now completed except for possible refinements. The second phase involved field investigations utilizing the instruments and techniques developed.

For these tests, the explosive charges fired varied between 600 and 4000 lb and records have been obtained to distances of 350 km. The amplitudes observed depend not only on charge weight and distance but also on the degree of coupling of explosive charge and seismometer with solid bedrock. In addition, apparent abnormalities can be obtained from the simultaneous appearance of several phases. In general, the amplitudes of first arrivals betwen 100 and 400 km lie between 10^{-6} and 10^{-8} cm and apparent frequencies between four and ten cm/sec. Under very favorable circumstances, that is, a minimum of man-made disturbances and effects of winds blowing against neighboring obstructions, seismic amplitudes down to almost 10^{-8} cm can be observed by means of frequency discrimination.

From time-distance curves obtained by refraction observations, it appears that the following layering depth and compressional-wave velocities occur below the region in the vicinity of Washington, D. C.: 0-10 km, velocity 6.0 - 6.17 km/sec; 10-24 km, 6.7 km/sec; 24-42 km, 7.05 km/sec; 42-? km, 8.15 km/sec. The apparent predominant frequencies of these wave trains appear to lie between four and 15 cm/sec.

Results from reflection shooting are more conflicting because they are able to show up finer details of structure. The grosser aspects as portrayed above appear, however, to be corroborated. This investigation of reflection observations, and in particular of vertical reflections, is expected to be vigorously pursued. To this end, limiters have been incorporated in the output stage of the amplifiers to protect the recorder pens and yet maintain high gains for observation of later arrivals. No intensive investigation has been made of the shear and surface waves which tend to overlap at distances out to 300 km. However, a preliminary survey shows that these are of considerably longer period and have velocities approximating those calculated on the assumption of 1/4 for Poisson's ratio.

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STUDY OF THE BLOCKING-ACTION WEATHER PROCESS

Robert D. Elliott

Abstract--This paper is a resumé of the more interesting highlights of a partially completed Office of Naval Research - California Institute of Technology research project on the blocking-action weather processes which has been under the author's supervision and has engaged the part-time attention of T. Smith and L. Crow of the staff of the California Institute of Technology Meteorology Department during a period of nine months or so.

Blocking action is defined and the geographical distribution and variation in frequency of occurrence from year to year during the January-February season discussed. The basic data used are surface pressures at 10° intersections in the region 35°-60°N and 140°E through 180° to 40°E. The Northern Hemisphere Historical Sea-Level Map Series is the data source.

The westerlies are then treated as a broadscale lateral turbulence phenomenon with the migratory cyclones and anticyclones representing turbulent eddies which exchange heat between tropical and polar regions. It appears that blocking action represents a state of abnormal mixing and that in years when blocking action is excessive, the northward heat transport is excessive and vice versa.

Some details of blocking action are outlined for blocking highs having a point of inception in the region 50° to 60°N and 0° to 25° W. Several prerequisites for blocking action are observed during the 15-day period prior to inception. Involved effects appear to develop subsequent to inception at points both upstream and downstream as far away as 180° of longitude and as late as 20 days after the inception date.

Work thus far completed on the blocking-action project being conducted at the California Institute of Technology under contract with the Office of Naval Research has revealed some interesting results, and although it is premature to discuss them in full at present, a short preliminary report is given below.

Blocking action is a term in fairly common usage by extended forecasters, and may be defined for the purposes of this paper as a condition where the more or less zonal flow of the westerlies is interrupted in a sector or sectors by strong, persistent, meridional type flow. Synoptically the condition is characterized by the development of persistent high pressure at high latitudes in such manner as to obstruct the normal eastward progress of migratory cyclones and anticyclones. In the middle troposphere pressures and temperatures are considerably above normal over the high-pressure region, while in the stratosphere pressures are above normal and temperatures below normal. The high-pressure development is linked, as a rule, to simultaneous, abnormally deep depressions either upstream or downstream, or both, which are often trapped at rather low latitudes.

The general objective of this project is the investigation of the role of blocking action in the Northern Hemispheric circulation and its relation to the circulation patterns occurring prior and subsequent to its inception. In order to accomplish this, a long series of data is required. This has necessitated the use of the 40-year Northern Hemisphere sea-level historical weather maps [JOINT METEOROLOGICAL COMMITTEE] as the basic data source. The region under consideration has been in the band of the westerlies 35°N to 60°N and from 140°E through 180° to 40°E including the Pacific, North America, the Atlantic, and Europe. Daily surface pressure values at 10° intersections form the basic data.

Using an objective criterion for defining blocking action in terms of the persistence of abnormally high pressures at high latitudes, the geographical distribution of the frequency of blocking-action occurrence was determined. This showed the most frequent occurrences in the East Pacific and East Atlantic.

Year to year variations in the occurrence of abnormally high pressure at high latitudes for the January-February season of the 20 even years were found to have a sinusoidal shape with a period of roughly 12 to 14 years. This was compared to the sunspot curve for the January-February season of the same years and it was found that the two were in phase for about two

cycles but that the third cycle was completely out of phase. The existence of this long-term climatic swing is quite interesting and suggests parallel changes in other circulation characteristics.

Since meridional type flow is extreme during blocking action, a reasonable hypothesis is that the heat exchange across the westerlies between tropical and polar regions is excessive during years with an excess of blocking action and vice versa. To test this hypothesis, it was necessary to apply the turbulence concepts of fluid mechanics to the westerlies in order that the heat exchange could be evaluated from data of the type being used. As early as 1921, DEFANT [1921] treated the stream of the westerlies as a current within which broadscale lateral turbulence in the form of unstable, migratory cyclones and anticyclones accomplished the lateral transport of various properties such as momentum and heat. Later treatments along this line have been made by LETTAU [1935], ROSSBY [1938], and others.

The first requirement in this approach is the determination of the exchange coefficient for heat and then, from the north-south thermal gradients, the northward heat transport at the surface may be obtained. It appears from numerous investigations that it is reasonable to assume the exchange coefficient for momentum (eddy viscosity coefficient) is proportional to and even identical with that for other properties. Therefore, there being a relatively simple method available for the computation of the eddy viscosity based upon the variability in the north-south geostrophic wind, this assumption was made.

The mean eddy viscosity coefficients at each point in the area under investigation were determined for each of the January-February seasons of the 20 even years. A map showing the distribution of mean viscosity coefficients for the 20 years agrees with those determined for single seasons by previous investigators. It shows a maximum in mixing along the mean polar front, especially just east of the Aleutian and Icelandic Lows where values of 1.3×10^8 g/cm/sec appear in contrast to values as low as 0.5×10^6 near 35°N. The mean period of the eddy motion shows a similar geographical distribution with a maximum value of nine days in the Bristol Bay region and minimum values of just under five days in Eastern United States and off the east coast. The overall mean mixing length is 8.2×10^7 cm which compares favorably with the size of migratory cyclones and anticyclones.

Summing the eddy viscosity values over the entire area under investigation for each season yielded an index of mixing which showed a year to year variation closely paralleling that for blocking-action occurrences.

Due to the fact that surface thermal gradients are a maximum along the band of maximum mixing, the northward heat transport shows a geographical distribution resembling that for the eddy viscosity coefficient. Year by year values of the seasonal mean thermal gradient were not available over the oceans, but were for North America since 1916. The year to year variations in northward heat transport in North America showed evidence of paralleling those of the eddy viscosity coefficient and it is highly probable that the same thing occurs over the ocean areas. If this is true over the entire Northern Hemisphere, the northward heat transport in the January-February season may vary as much as 20 per cent from year to year.

Evidence has been gathered showing that the year to year variations in the mixing parallel the year to year variations in the north-south thermal gradient across the westerlies. Thus, in years with sharper mean gradients the mixing is in excess of normal. This indicates that probably the radiative properties of the Earth and its atmosphere vary from year to year to a considerable extent. This causes a large variation in the thermal gradient, which would be even greater were it not for the partial compensation resulting from the fact that the excessive gradient stimulates the westerlies to greater mixing resulting in a somewhat greater heat exchange between tropical and polar regions.

South of the mean polar front, evidence favors the transport of much heat in latent form. JACOBS' [1942] charts of heat loss to the atmosphere by the oceans show values of losses from the ocean of the order of 500 to 1000 calories per cm^2 per day just off the east coasts of the continents. This becomes real heat along the polar front and sharpens thermal gradients there. Across the polar front heat transport through turbulence becomes the major effect. A rough comparison between heat transport in this region and that required according to SIMPSON'S [1928] studies of the heat budget of the atmosphere shows that the mixing layer need be only about two km thick. In view of other evidence regarding the decrease of thermal mixing aloft it might be more proper to say the coefficient has one e^{th} of its surface value at two km, assuming an exponential decrease with height.

Assuming straight westerlies, and an east-west orientation of the mean isotherms, the heat convergence or gain can be computed from the fields of temperature and mixing coefficients. Charts showing the geographical disposition of this quantity were prepared and showed general agreement with the heating as determined by WEXLER [1944] for the first 10,000 feet of the atmosphere based upon the determination of the advection term. The most notable disagreement occurs just off the East Coast of the United States.

Since the eddy viscosity coefficients, the mixing lengths, and the eddy periods are larger during periods of excessive blocking action it would appear that blocking action represents a different class of eddy motion than that of the ordinary migratory cyclones and anticyclones. Also the depth of mixing is apparently much greater in the case of blocking action where closed centers appear up into the stratosphere. Once a blocking high cell forms, it must in general represent an accumulation of warm tropospheric air (in spite of the presence of a cold shielding layer adjacent to the surface) at high latitudes which is gradually mixed with the cold surroundings through the action of the broadscale turbulence represented by migratory cyclones and anticyclones moving along its periphery.

Thus far, 24 cases of blocking action originating in the region 50°-60°N and 0°-25°W have been investigated in various ways, especially through the use of a series of three-day mean maps showing the sea-level pressure departure from normal for the period from 15 days prior to the inception of blocking action through 20 days following blocking action. It was found that the cases were of two classes: High latitude blocking, in which the blocking action is effective at high latitudes and involves a merging or "connection" with a polar high to the north; and low latitude blocking in which the blocking action consists mainly of a northward shift of the general westerly flow. The three-day mean pressure departure charts for all the cases in each class were averaged.

A series of significant and apparently physically connected events leads up to and follows the inception of blocking action. Points of interest are:

(1) In both high and low latitude blocking, an abnormal strength in the zonal flow just south of Iceland exists at least 15 days prior to inception and reaches a maximum about nine days prior to inception. It is believed that this is associated with an increased north-south thermal gradient across the region.

(2) In both high and low latitude blocking, the development of low pressure downstream occurs in Russia during the week to ten days prior to inception.

(3) In low latitude blocking, above normal pressure is found in the northeastern part of the Pacific zone (and in Alaska), and Alaskan temperatures are below normal, during the week leading up to inception.

(4) In high latitude blocking, low pressure develops upstream in the western part of the Atlantic zone and in Eastern Canada a few days prior to inception.

(5) In low latitude blocking, pressure increases in the Midwest and in the Central Atlantic States three to five days following inception, and a marked fall in temperature at Chicago and Nashville from the second to the fourth day following inception. This indicates a polar outbreak in this region at this time.

(6) In high latitude blocking, low pressure develops in the Azores region south of the blocking high three to five days after inception. This shows a tendency for cold-centered lows to become trapped in this area.

(7) In high latitude blocking, a very significant area of below normal pressure develops in the southeastern part of the Pacific Zone approximately in the area 35°-50°N and 125°-175°W, 12 to 14 days after inception.

(8) In low latitude blocking, high pressure develops in the northern part of the Pacific Zone (and in Alaska) 15 to 20 days after inception.

A review of the Northern Hemisphere charts for each of these weather processes showed that apparently a stationary wave pattern developed downstream from the inception point. A definite trough exists in western Siberia and the eastern Siberian High increases in pressure. In both types of blocking action outbreaks of cold Siberian air move across the Bering Straits and

into Alaska, about 10 to 15 days after inception in the case of high latitude blocking, and about 15 to 20 days after, in the case of low latitude blocking. Upstream effects do not appear to be as marked as had been expected but the synoptic charts indicate that polar easterlies strengthen in North America following inception of high latitude blocking but generally at latitudes north of 60°N.

The problem is being treated theoretically by investigating the effects produced by inserting a cylinder into a straight west-east current on a rotating Earth. This model is quite analogous to the insertion of a blocking action high into the stream of the westerlies and it is hoped that in this way some light will be shed upon the problem.

The causes for the development of the blocking High are still obscure. It is felt that in view of the presence of low temperatures in Alaska prior to inception, and because of its weaker character, low latitude blocking is probably a secondary effect. In the case of high latitude blocking perhaps the increase in north-south thermal gradient in the Atlantic is an important factor in its production and it is intended that this be investigated.

In conclusion, progress thus far on the project has resulted in the accumulation of certain evidence indicating the existence of Hemisphere-wide and long-period weather processes resulting from a disturbance of the westerly flow by the presence of persistent, large-scale blocking-action eddies.

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EVOLUTION OF MONTHLY MEAN CIRCULATION AND WEATHER PATTERNS

Jerome Namias

Abstract--Two important conclusions derived from a six-year experiment in the preparation of monthly mean forecasts are discussed. These are (1) that regardless of how they are made up, monthly mean charts, particularly those constructed for mid-troposphere levels, to a large extent determine monthly mean temperature and precipitation anomalies; and (2) monthly mean mid-troposphere flow patterns of the general circulation, when treated on a hemisphere-wide scale, undergo an orderly evolution and development which can be rationalized at least qualitatively by use of physical and kinematical principles. The second of these conclusions poses vast problems and indeed opens up a new vista for the dynamic meteorologist. Some speculatory hypotheses are suggested.

Meteorological institutes over the world for many years have prepared monthly weather summaries. In some cases these have included mean maps of atmospheric pressure and temperature at the surface and aloft. A casual comparison of these maps with the corresponding weather anomalies particularly of the surface temperature and precipitation will readily convince one that mean pressure patterns are closely associated with weather anomalies. This general conclusion has been known at least since 1881 when Teisserenc de Bort emphasized the importance of centers of action of the general circulation. Indeed, the predominant role of the Bermuda High on weather of the eastern United States is known even to the newspaper-reading layman.

Although the role of the centers of action in governing weather has been realized for many years, little progress has been made in forecasting their month to month behavior. For the most part, studies relating to this problem have been concerned with statistical time-lag relationships in which a connection is sought between certain indicators of the strength and position of the centers of action and subsequent long-period weather anomalies [WALKER and BLISS, 1930]. Investigations of this nature have often been hampered by lack of data, and attempts have sometimes been made to characterize a circulation pattern by a few numerical values supposedly describing a map. During the past ten years, more and better data have been made available to help solve these problems. One prominent source of information is the 40-year series of daily Northern Hemisphere sea-level weather maps [JOINT METEOROLOGICAL COMMITTEE] from which monthly mean sea-level pressure maps and normals have been computed. Another, perhaps more important source, is the vast aerological network established over the Northern Hemisphere. These data have made possible the construction of monthly mean contour and temperature charts for the 700-mb level on a hemispheric scale and provide the basis for a synoptic-statistical attack on the problem of long-range weather forecasting.

In view of the fact that some degree of success had been achieved in forecasting five-day mean circulation patterns, and that a rational theory of the behavior of the centers of action had been developed [ROSSBY, 1939], the author, in 1942, began an experiment in forecasting monthly mean circulation patterns and associated weather phenomena. This experience and development has led to a complex but fairly definite methodology for preparing monthly forecasts. These forecasts have some small but definite degree of skill and are now available to the public through government subscription. An extensive paper dealing with this methodology is planned. The purpose of this preliminary report is to bring to light two of the most striking and far-reaching conclusions of this experiment:

(1) Regardless of how they are made up, monthly mean circulation charts, particularly those constructed for mid-troposphere levels, to a large extent determine surface weather anomalies.

(2) Monthly mean mid-troposphere flow patterns of the general circulation undergo an orderly evolution and development which can be rationalized by use of physical and kinematical principles.

These two concepts hold out the hope for successful average monthly weather forecasts.

In practical weather forecasting the two concepts mentioned above are generally used in the reverse order of that expressed; that is, a forecast of circulation patterns is made first, and then

weather anomalies are derived from these patterns. In order to make this second step more objective and to prove its feasibility with mean charts covering periods as long as a month, a research project was recently set up in the Extended Forecast Section of the United States Weather Bureau to determine the relationship between mean monthly 700-mb contour charts and the corresponding anomaly of surface temperature over the United States. In earlier work [NAMIAS, 1947a] this step had been performed in a qualitative manner by considering chiefly the anomaly of the flow pattern. After constructing lines of equal anomaly of 700-mb contour an estimate of temperature anomaly could be made by determining the gradient air flow relative to the normal. For example, wind from south relative to normal generally brings warm weather; wind from the north, cold. An example is shown in Figure 1. As illustrated by this Figure, temperature anomalies are analyzed in terms of above and below normal, near normal, and much above and much below normal. The numerical limits which define these ranges of temperature, called class limits, are based on a statistical analysis of past records through which is determined the normal frequency of occurrence of temperatures at various times of the year for different locations. The classes above, below, and near normal are so defined that they each normally occur one-fourth of the time; and the classes much above and much below normal, one-eighth of the time. For precipitation, the terms used in forecasting are light, moderate, and heavy, each class normally occurring one-third of the time and thereby having equal probability of occurrence. Obviously, the class limits vary from month to month and from place to place. There are obviously many

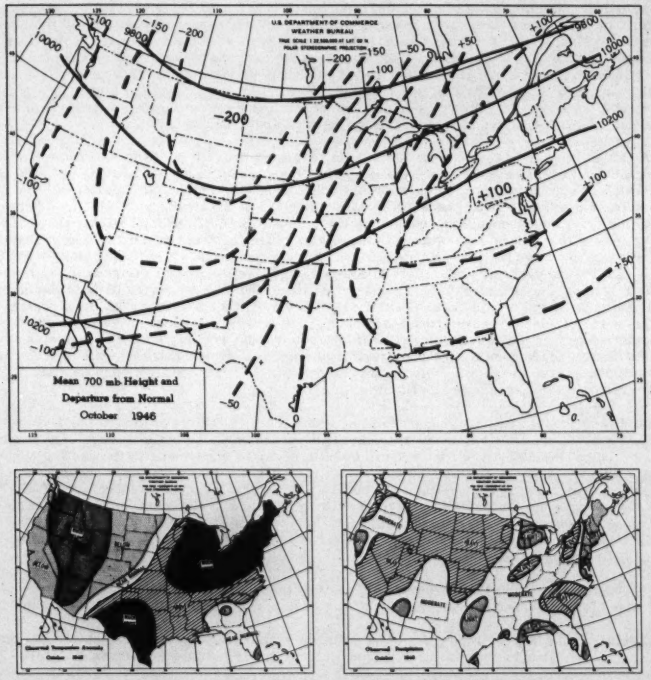

Fig. 1--Mean contours (solid lines) with isopleths of anomaly at 700 mb (broken lines) and corresponding temperature (lower left) and precipitation anomalies (lower right) for October 1946

ramifications in the use of this technique since the effect of coastlines, mountain barriers, and other features must be taken into consideration. Another factor related to the surface temperature anomaly is the absolute magnitude of the 700-mb height anomaly. This relationship is in the sense that surface temperature anomaly correlates positively with the 700-mb contour anomaly. There are numerous physical and statistical reasons why such a correlation exists, but these will not be discussed in this brief report. In order to put these considerations into a more objective form, the two parameters vector wind velocity and height at 700 mb, both taken relative to normal, were related to the temperature anomaly observed at the surface. These relationships were found for each of 25 stations in the United States for each season of the year by methods of graphical correlation. Examples of monthly mean temperature estimates made by these methods when applied to observed 700-mb charts are shown in Figure 2 along with the observed temperature anomalies they are supposed to resemble. A test of this objective method on six months of independent data at 15 stations showed that of five classes of temperature anomaly noted above, objective temperature anomaly estimates made from observed 700-mb maps were either correct or only one-class in error 96 per cent of the time.

Estimating precipitation from mean 700-mb patterns is more difficult. Consequently this problem is in a much less satisfactory stage of development. However, a thorough study for the Tennessee Valley area by KLEIN [1948] has resulted in development of a reasonably dependable model (Fig. 3) relating the mean 700-mb contours to precipitation in eastern United States in winter, and presumably in other areas where the terrain is not mountainous and where adequate sources of moisture lie to the south. Essentially this model shows that heavy precipitation is to be expected east of the upper level trough and in areas of confluence [NAMIAS, 1947b]. Light precipitation is found principally behind troughs and ahead of ridges. Statistical tests on independent data for the Tennessee Valley area have confirmed the association of precipitation anomaly with mean 700-mb pattern.

These results can leave little doubt that, regardless of the sequence of events within the monthly period, the mean 700-mb contour patterns to a large extent define the average weather characteristics of the month.

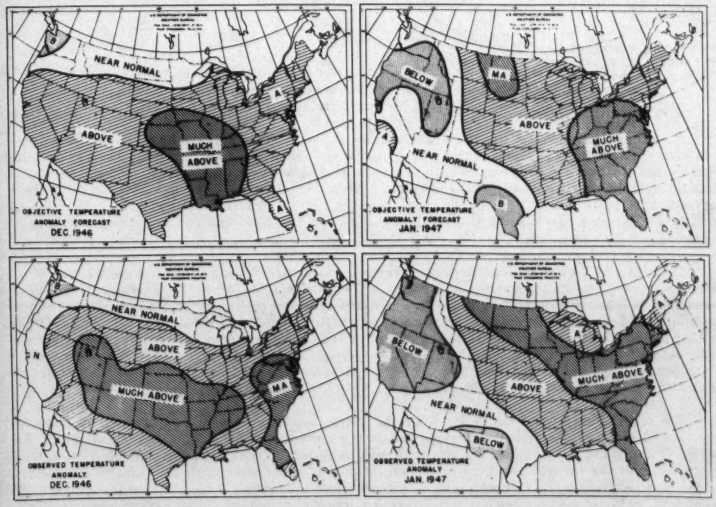

Fig. 2--Comparison of observed surface temperature anomalies (lower figures) with objective temperature estimates (upper figures) made from observed 700-mb monthly mean charts

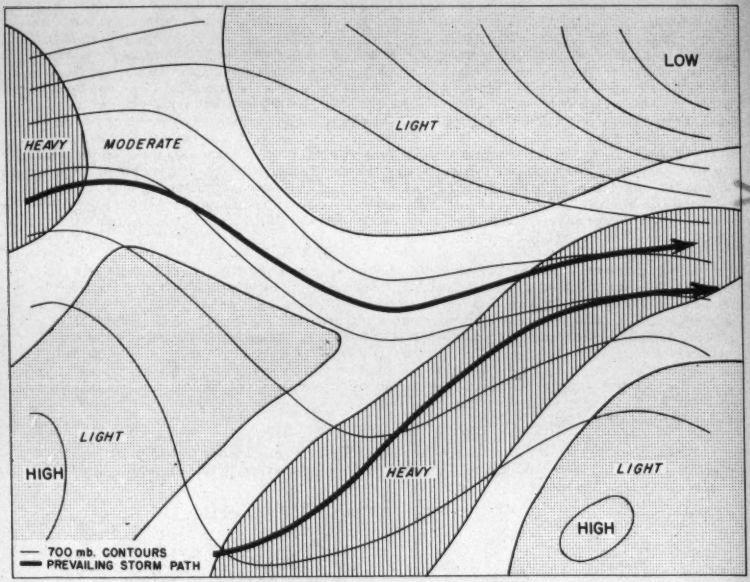

Fig. 3--Schematic model for winter precipitation associated with 700-mb contour charts (after Klein)

An attempt will now be made to illustrate the second concept that the mid-troposphere flow patterns undergo an orderly evolution and development which lends itself to physical and kinematical rationalization. In order to do this, two periods will be described, one extending from the middle of March through July 1945, and another from December 1947 through March 1948. These periods have been chosen because the mean monthly 700-mb charts show a rather clear-cut continuity and because they offer a rational explanation of some economically important though very puzzling weather anomalies observed over the United States.

Figures 4 to 7 show the monthly mean 700-mb charts and associated anomalies of temperature and precipitation for the period December 1947 through March 1948. This period was characterized by abnormal East Coast storminess during January (and also the last week in December) of which all New Yorkers are acutely aware; and unprecedented drought in California through the winter which was not substantially relieved until March (see anomalies of Figs. 4 to 7). Another interesting feature is that temperature anomalies over the country were essentially reversed from January to March. Whereas January was cold in the East and warm in the West, March was warm in the East and cold in the West.

The monthly mean 700-mb charts show that these long-period weather characteristics were associated with an orderly retrogression (westward movement) of a mean trough from off the Atlantic Coast in December to off the Pacific Coast in March. Trough lines are denoted by solid heavy lines drawn through points of minimum latitude of successive contours. Heavy arrows show in monthly displacements the continuity of the principal trough and ridge. As the trough proceeded westward, cold air masses feeding into its rear portion resulted in a progressive westward displacement of the area of subnormal temperature. The prevailing band of storminess and precipitation, occurring east of the trough, likewise proceeded westward, finally breaking the California drought in March.

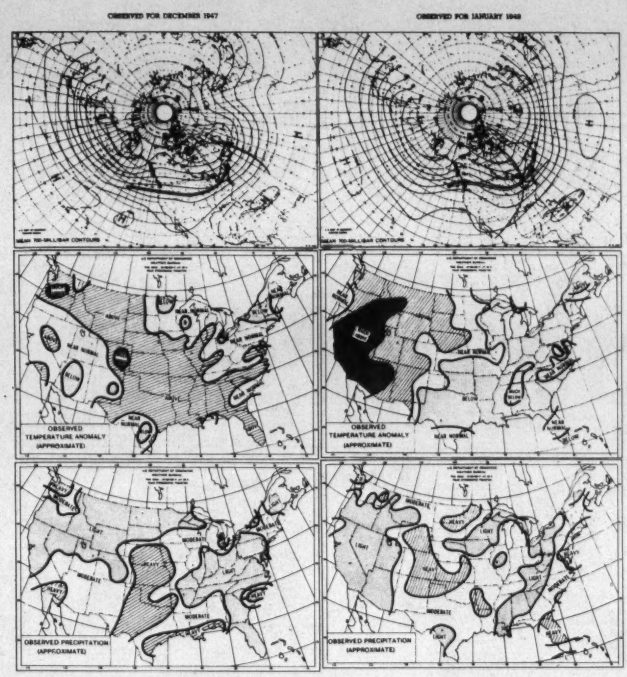

Fig. 4 Fig. 5

Figs. 4-5--Monthly mean 700-mb contours and temperature and precipitation anomalies for December 1947 and January 1948; open double lines show vorticity trajectories; solid arrows, monthly continuity of trough and ridge lines

Corresponding charts for the period in 1945 are shown in Figures 8 and 9. Here, in order to clarify the continuity, the monthly mean maps are illustrated from mid-month to mid-month as well as for calendar months. The temperature and precipitation anomalies are reproduced from the Monthly Weather Review. The principal weather characteristic of economic importance during this period was the persistent wet, cool spring and early summer in the corn belt (central mid-west), which delayed planting operations to a threatening degree. Another interesting feature was the sudden reversal of temperature anomalies from cold in the West and warm in the East during April to warm in the West and cold in the East in May. This abrupt change led to damaging late spring frosts which injured prematurely developed fruit trees in the East. Also the excess and persistent rainfall in July along the East Coast is of especial interest. For example, at Washington, D. C., rainfall amounted to ten inches compared to a normal of 4.6 inches. Here the continuity of the 700-mb mean charts shows consistent eastward motion of trough and ridge systems over the United States. The trough extending from the Dakotas to New Mexico during the period mid-March to mid-April advanced eastward to the Atlantic Coast by May. The newly formed trough just along the West Coast in May advanced gradually eastward to the Appalachians by July. These two troughs were largely responsible for the weather peculiarities described above.

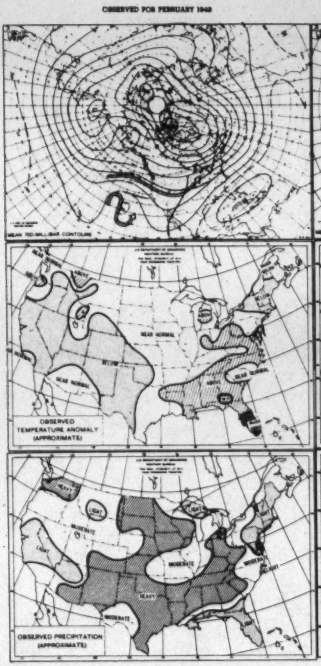

Fig. 6

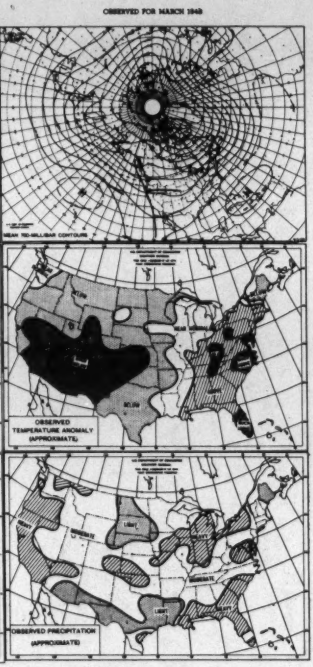

Fig. 7

Figs. 6-7--Monthly mean 700-mb contours and temperature and precipitation anomalies for February and March 1948; open double lines show vorticity trajectories; solid arrows, monthly continuity of trough and ridge lines

Two periods showing different characteristics of trough motion have been illustrated. In the first series of charts (Figs. 4 to 7) the motion was westward, and about three months elapsed while the trough moved from off the Atlantic Coast to the Pacific Coast. This was about 75°W longitude in the latitude of 45°N. In the second series (Figs. 8 and 9) eastward trough motion prevailed. Each of the troughs moved about 45° of longitude in two months. These different characteristics of motion appear to be associated with the wavelength between the moving trough and the succeeding trough to its west, just as with troughs on 5-day mean maps [NAMIAS and CLAPP, 1944]. Thus in the 1947-48 winter series, where retrogression prevailed, the wavelengths are long; in the 1945 series they are short. In the 1945 series short wavelengths are maintained by development of a new trough along the West Coast in May.

In a qualitative manner the trough motions appear to agree with the general expression of ROSSBY [1939]

$$c = U - \beta L^2/4\pi^2 \qquad (1)$$

relating the velocity c of the trough to the zonal wind speed U and the wavelength between troughs L. The term β is the northward rate of change of the Coriolis parameter.

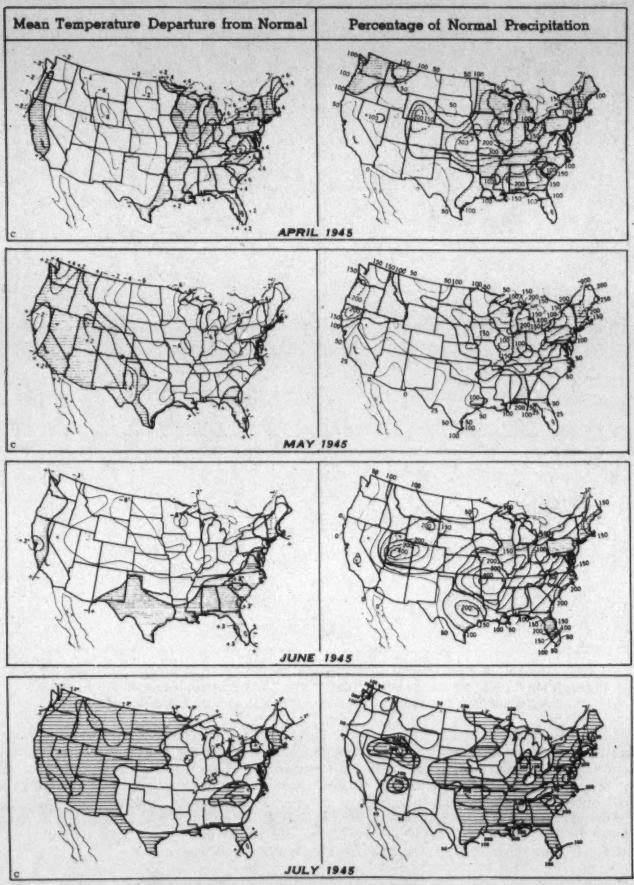

Fig. 8--Temperature and precipitation anomalies for the months April-July 1945; departure from normal of temperature in degrees Fahrenheit and precipitation in percentage of normal

This expression for motion of waves in the westerlies was based on the principle of conservation of the total absolute vertical component of the vorticity. Constant vorticity trajectories based on the same principle have been constructed for certain points in Figures 4 to 9. These points have been selected in areas of practically no curvature and little shear in order to simplify the computations and to shed some light on the nature of troughs whose motion has been discussed. In the 1945 series where eastward motion prevailed, for the most part the computed vorticity paths indicate troughs ahead of the observed troughs in the contours. A noteworthy

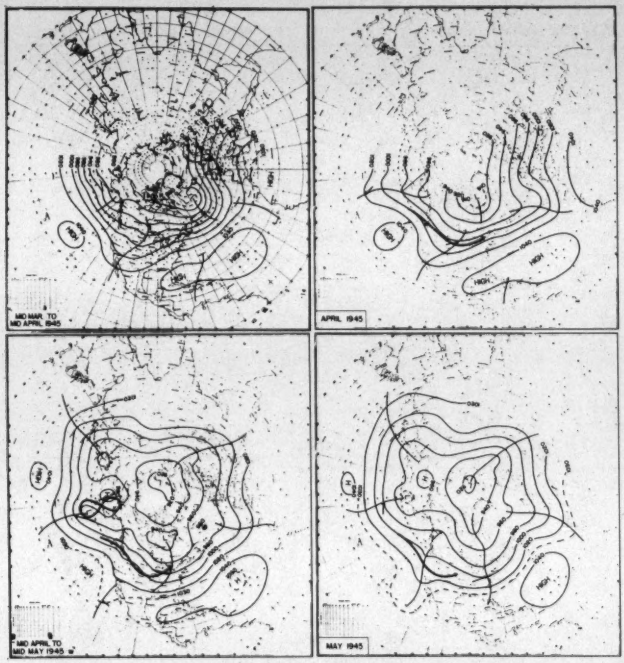

Fig. 9(a)--Monthly mean 700-mb charts, constructed twice a month from mid-March through May 1945; vorticity trajectories are shown as double open lines; solid arrows show continuity of certain troughs and ridges from map to map

exception appears on the mid-April to mid-May chart, where the trough computed from vorticity considerations lies far behind the observed trough, indicating the unstable condition of super-stationary wavelength which often precedes the formation of a new trough. In the mid-May to mid-June map the trough in the contour is practically in the same place as that indicated by vorticity and yet the trough subsequently moved eastward. This apparent inconsistency appears to be due to the pronounced increase in zonal wind speed off the coast of Washington and Oregon during June. In the 1947-48 series, where retrogression occurred, the vorticity trajectories predominantly indicate troughs behind the simultaneously observed troughs.

It appears from this series of charts that vorticity computations made on monthly mean 700-mb charts tend to indicate the general nature of the subsequent month's change in flow patterns and thereby may be of some prognostic value. If this is true (and it certainly requires more proof than the few selected cases shown here), it poses highly important problems. Generally, a mean chart constructed for a time interval as long as a month has been considered to represent a steady state in which isobars, streamlines, and trajectories coincide. Under steady-state assumptions, the deviations of the computed vorticity trajectories from the contours in the 1945 and 1948 map series must be considered as due to persistent or predominating geographically fixed areas of convergence and divergence. In fact, applying this thesis to normal (long-period average) 700-mb charts, NAMIAS and CLAPP [1946] were able to construct normal fields of convergence and divergence for much of the Northern Hemisphere. If individual monthly mean charts

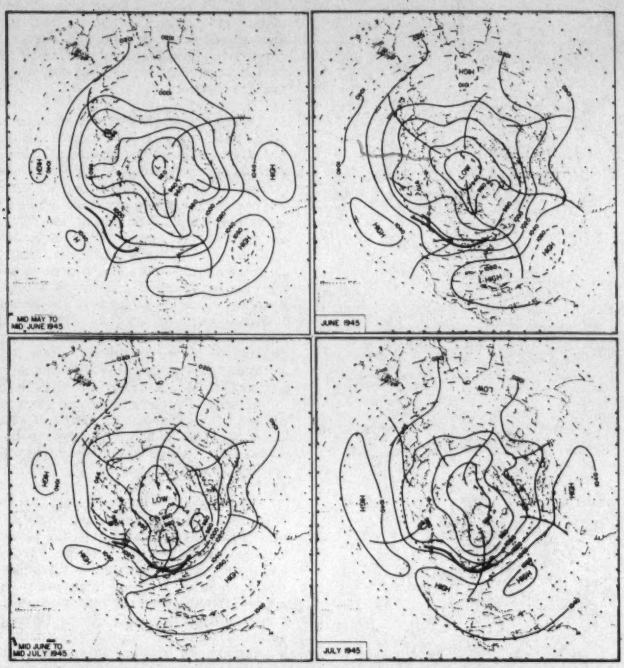

Fig. 9(b)--Monthly mean 700-mb charts, constructed twice a month from mid-May through July 1945; vorticity trajectories are shown as double open lines; solid arrows show continuity of certain troughs and ridges from map to map

represent steady state conditions, then by definition the vorticity paths have no prognostic value, wavelength criteria do not apply, and the deviations of vorticity trajectories from contours must be explained in terms of semi-stationary fields of convergence and divergence. These two series of charts, plus the author's six years of experience with monthly forecasting, has left the definite conviction that wavelength and vorticity consideration can be applied at least qualitatively to monthly mean 700-mb charts. However, statistically acceptable proof is as yet lacking. (Data are currently being assembled in connection with such a project.) Granting that this conviction is correct, the monthly mean chart must be viewed not as a haphazard static average of some 30 days of maps but rather as a physical and dynamic entity which contains within it seeds for the germination of a new pattern.

If monthly mean maps are averaged for a given month for a large number of years, a normal for that month is obtained. Such charts at 700 mb and sea level for the month of January are shown in Figure 10. The normal charts show preferred sites of ridges and troughs in the mid-troposphere and the corresponding centers of action at sea level. In any given month an exact duplicate, or even marked resemblance, to the normal over the entire hemisphere is seldom observed. In other words, there are usually large aberrations of monthly mean circulations from the normal state in one or more areas of the hemisphere. It is a well-known fact, emphasized recently by TANNEHILL [1944] and WILLETT [1948] that the variability of long-period values (such as monthly means) is much greater than would be obtained from a randomly selected series

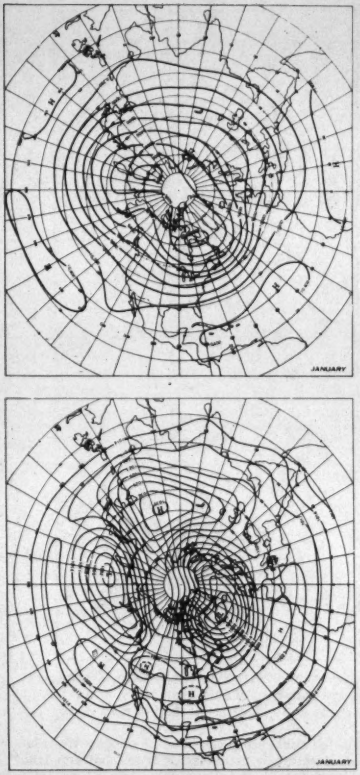

Fig. 10--Normal contours at 700-mb (above), and normal sea-level isobars for January

of data. We are then faced with highly persistent circulations, or, to use Willett's more appropriate term, persistently recurrent circulations, which become manifest on long-period means as large anomalies of the general circulation.

What causes these circulation anomalies? Why do they appear to undergo a quasi-orderly movement and apparently obey the physical laws established for instantaneous maps? In spite of the fact that the correct answers to these two questions will go far to solve long-range forecasting, satisfactory answers are not yet available and probably will be slow in coming. In speculating upon the answers the author must draw heavily upon twelve years of experience with atmospheric circulation patterns of the Northern Hemisphere. For one thing, this experience leaves absolutely no doubt that changes in the circulation in one part of the hemisphere have a profound effect upon circulations in other parts. This idea is probably almost as old as the science of meteorology, but somehow has not been fully accepted or realized. The manner in which such hemisphere-wide disturbances of the general circulation might operate is shown schematically in Figure 11.

In Figure 11(A) a schematic pattern has been drawn to represent roughly the normal mid-troposphere flow pattern for January. This pattern has essentially three troughs and three ridges. Let us now introduce into this circulation a strong disturbance which appreciably deepens the central Eurasian trough. This marked deepening, through the action of vorticity, begins to affect the area downstream by building up systems with increasing amplitude and decreasing wavelength. It also affects the area upstream by means of the well-known but as yet inadequately explained blocking action [NAMIAS, 1947a, ELLIOTT, 1948] where strong ridges and upper level highs are developed to the north and cyclones are deflected to the south. After some time the spread of energy upstream and downstream can increase amplitudes and shorten wavelengths to such an extent that there is an increase in the total number of troughs in the hemisphere to four as shown in (B). A further time interval might result in the pattern (C) where five troughs are indicated. The continuity of these maps is meant to be interpreted so that in (B) a new low latitude trough is formed through the deflection of west-to-east-moving cyclones south of the blocking activity; this may eventually crystallize into the pattern of a warm Scandinavian High over a cold Mediterranean Low (C). The transfer of energy downstream from the initial disturbance may shorten wavelengths sufficiently so that a Bering Sea ridge taps the extremely cold Alaskan air leading to the formation of the Gulf of Alaska Low [NAMIAS and CLAPP, 1944]. The evolution of the radically different final circulation (C) from the original state (A) has been accomplished by the introduction of only one initial disturbing force shown by the large asterisk.

From year to year there appear to be large circulation-disturbing forces at work. Unfortunately the areas in which these forces operate change from one year to the next. There may be and probably is more than one area of disturbance. And to make things still more complex, each

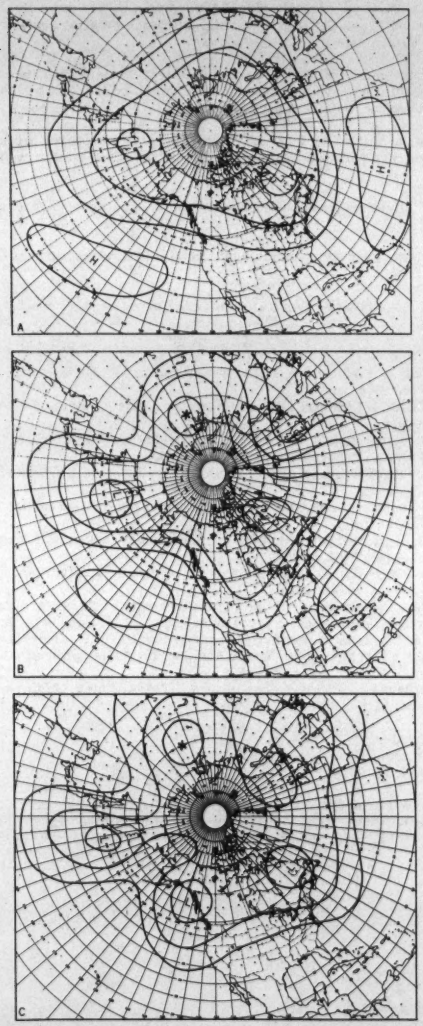

Fig. 11--Schematic mid-troposphere flow patterns (for example, 700-mb contour patterns) illustrating a feasible evolution of a highly anomalous circulation pattern (C) from an initial normal state (A) through introduction of a disturbance deepening the Eurasian trough (at asterisk)

disturbance attempts to set up a certain circulation pattern up and down stream from it. The areas caught in between two such large areas of disturbance must be zones where complex interference patterns result.

The paramount problem of what causes original large-scale disturbances remains to be solved. Several possibilities have suggested themselves to meteorologists throughout the past century. Some of the more prominent suggestions are:

(1) Extraterrestrial influences upon the Earth's upper atmosphere, particularly the effect of variations in the energy of selected bands of the Sun's spectral radiation on the atmosphere's ozone layer.

(2) Terrestrial influences, particularly variations in snow cover and temperature of ocean currents.

(3) Variations in the character and amount of nuclei of condensation and/or other atmospheric suspensoids.

A discussion of those possibilities lies outside the scope of this report.

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CHANGES IN THE NORTHERN HEMISPHERE SEA-LEVEL CIRCULATION IN THE 40-YEAR PERIOD 1899-1939

G. W. Brier

Abstract--A statistical study of the monthly mean sea-level pressure maps from 1899 to 1939 reveals that a decreasing trend in the average pressure over the Northern Hemisphere was present in each month of the year. A positive correlation was found between the time of occurrence of successive seasonal maxima and minima of pressure but there was no marked tendency for the maximum or minimum values of pressure to occur earlier or later in the season during the 40 1/2-year period. Trends in the distribution of sea-level pressure were studied by means of circulation pattern indices based upon zones showing the greatest normal seasonal change in pressure. New maps of normal sea-level pressure change from month to month are presented for the Northern Hemisphere.

The Historical Daily Map Series [JOINT METEOROLOGICAL COMMITTEE] has furnished 40 1/2 years of sea-level pressure data for the Northern Hemisphere. Pressures interpolated from these analyzed maps at specified intersections of latitude and longitude have been entered on punch cards, thus providing a large supply of data in a form useful for constructing various mean maps and for carrying out a number of investigations in meteorology and climatology. A preliminary analysis of these pressure data [BRIER, 1947] disclosed that during the period 1899-1939 there was a considerable decrease in the total mass of air over the Northern Hemisphere. These findings suggested that a more detailed examination of the long-time changes in the distribution of sea-level pressure by months or seasons might possibly provide some clues that would be useful in long-range weather forecasting or in explaining some of the climatic variations

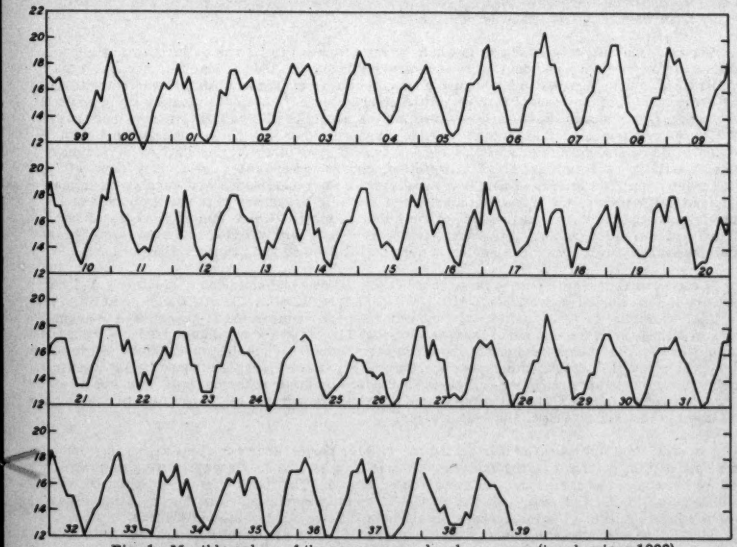

Fig. 1--Monthly values of the average sea-level pressure (in mb minus 1000) north of latitude 20°N for the period 1899 to 1939

Table 1--Regression coefficients showing trends in average pressure above 20°N latitude

Month	Regression coefficient (Mb/year)	Standard error (Mb/year)
Jan.	-0.027	.016
Feb.	-0.034	.016
Mar.	-0.033	.012
Apr.	-0.035	.010
May	-0.009	.008
June	-0.028	.008
July	-0.009	.010
Aug.	-0.008	.008
Sep.	-0.016	.008
Oct.	-0.016	.009
Nov.	-0.005	.011
Dec.	-0.007	.012

observed in the last half-century. This paper presents the results of some further studies that have been made using the series of monthly mean pressure maps [U. S. WEATHER BUREAU, 1946] that have been constructed from the data described above.

The average sea-level pressure above 20°N latitude has been determined for each month from January 1899 to June 1939 by a graphical integration of the area under the mean monthly pressure profile curves. These values, plotted as a time series in Figure 1, show the well-known seasonal variation in the mass of air over the hemisphere with high average pressure in the winter months and lower average pressure in the summer months. Several things of interest might be pointed out in regard to this curve. The actual month in which the maximum values occur varies from November to March while the minimum values occur in either June, July, or August. There was a tendency for the minimum values to occur earlier in the summer when the maximum value occurred earlier in the winter, the correlation between the months of occurrence of the maximum and the subsequent minimum being 0.38. However, the correlation coefficient between the month of occurrence of the minimum and the subsequent maximum was not statistically significant, being 0.25. During the 40-year period there seemed to be no marked tendency for the maximum or minimum values to occur earlier (or later) in the season.

The actual values of the maximum and minimum both show a decreasing trend during the period, the correlations with time being -0.52 and -0.40, respectively, both statistically significant. Next the individual monthly values were analyzed for trends, the linear regression coefficients with their standard errors being shown in Table 1. These results suggest that the trend toward lower average pressure over the Northern Hemisphere during the period was not confined to only a few months but was present in all seasons.

The question naturally arises as to whether this downward trend was uniform over the whole hemisphere or was more pronounced in some areas than others, thus producing a change in the circulation pattern. In order to study such pressure pattern changes an attempt was made to devise some indices of the general features of the circulation for each of the monthly mean maps of the period. It was thought that these pressure indices should be chosen in relation to those areas showing the greatest normal seasonal change in pressure, since it might be expected that such indices would be sensitive to long-period trends, as well as to other factors such as persistence or solar activity. Two indices, E and L, were then chosen and computed for each of the monthly mean maps from 1899 to 1939. Index E is a measure of the resemblance of a monthly mean map to the normal pattern of the preceding month and index L is a measure of the resemblance of a monthly mean map to the normal pattern of the following month. These indices were based upon average pressures for certain "key" areas that were chosen with relation to the centers of maximum pressure change shown on a series of normal month-to-month pressure change maps.

These normal pressure change maps, based upon the new maps of normal monthly sea-level pressure for the Northern Hemisphere [U. S. WEATHER BUREAU AND ARMY AIR FORCES, 1946] are shown in Figures 2 to 13, inclusive. Now consider, for example, the map showing the normal pressure change from September to October (see Fig. 11). Areas of maximum pressure rise are shown over the Asiatic continent and the western part of the United States, and centers of pressure fall appear in the Gulf of Alaska and near Iceland. Thus, on the average, it would be expected that monthly mean maps for September will be characterized by lower pressure over Asia and Western United States than October monthly mean maps. Likewise September maps will tend to have higher pressures in the Gulf of Alaska and near Iceland.

For each September and October during the 40-year period, four variables x_1, x_2, x_3, and x_4 were computed by determining the average pressure over each of four areas. Five points were used for each zone and their locations are given in Table 2. The location of these points, as well as others used in the study, are shown in Figure 11 by crosses connected with solid lines. Thus for a particular month, x_1 is the average pressure of the five points listed in the first two lines of Table 2. The next step was to take the differences $D_{12} = x_2 - x_1$ and $D_{34} = x_4 - x_3$ and plot a scatter diagram as shown in Figure 14. It is seen that there is very little overlap between the two groups, the dots clustering in the lower left and the crosses in the upper right. The slanting

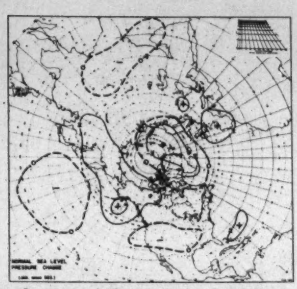

Fig. 2--Normal change in sea-level pressure over the Northern Hemisphere, January minus December (lines are drawn for each 2-mb pressure change)

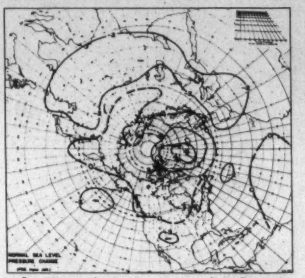

Fig. 3--Normal change in sea-level pressure over the Northern Hemisphere, February minus January (lines are drawn for each 2-mb pressure change)

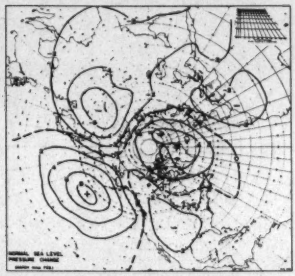

Fig. 4--Normal change in sea-level pressure over the Northern Hemisphere, March minus February (lines are drawn for each 2-mb pressure change)

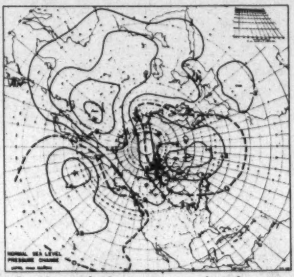

Fig. 5--Normal change in sea-level pressure over the Northern Hemisphere, April minus March (lines are drawn for each 2-mb pressure change)

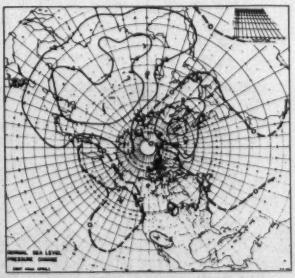

Fig. 6--Normal change in sea-level pressure over the Northern Hemisphere, May minus April (lines are drawn for each 2-mb pressure change)

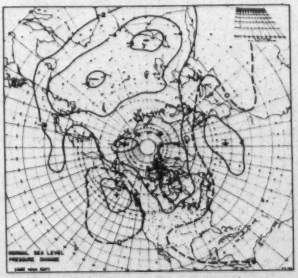

Fig. 7--Normal change in sea-level pressure over the Northern Hemisphere, June minus May (lines are drawn for each 2-mb pressure change)

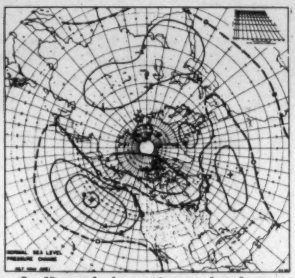

Fig. 8--Normal change in sea-level pressure over the Northern Hemisphere, July minus June (lines are drawn for each 2-mb pressure change)

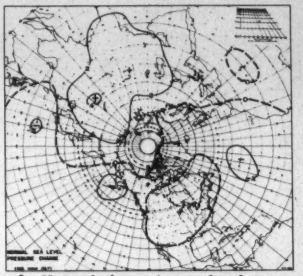

Fig. 9--Normal change in sea-level pressure over the Northern Hemisphere, August minus July (lines are drawn for each 2-mb pressure change)

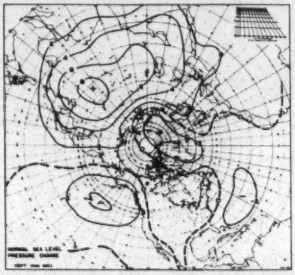

Fig. 10--Normal change in sea-level pressure over the Northern Hemisphere, September minus August (lines are drawn for each 2-mb pressure change)

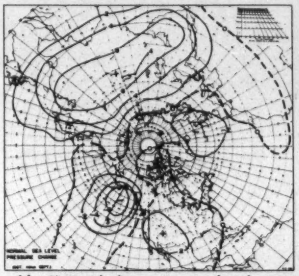

Fig. 11--Normal change in sea-level pressure over the Northern Hemisphere, October minus September (lines are drawn for each 2-mb pressure change)

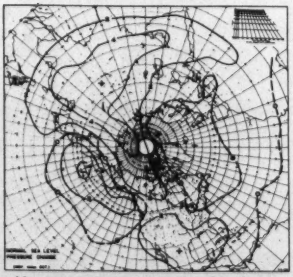

Fig. 12--Normal change in sea-level pressure over the Northern Hemisphere, November minus October (lines are drawn for each 2-mb pressure change)

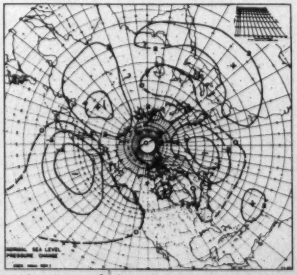

Fig. 13--Normal change in sea-level pressure over the Northern Hemisphere, December minus November (lines are drawn for each 2-mb pressure change)

Note: Points selected for indexing purposes are shown by crosses connected by straight lines in Figure 11.

Table 2--Location of points used in determining indices of circulation patterns

Variable	Location of points	
	Latitude	Longitude
x_1	55°N	5°W, 10°W, 15°W, 20°W
	60°N	0°
x_2	40°N	135°E
	45°N, 50°N, 55°N, 60°N	130°E
x_3	40°N, 45°N, 50°N, 55°N, 60°N	150°W
x_4	35°N	60°E
	40°N	65°E
	45°N	70°E, 75°E, 80°E

lines on this Figure were drawn in order that a parameter y_1, varying between 0 and 100, would be assigned to each month, depending on where it fell on this chart.

A similar scatter diagram was prepared using the average pressures x_5, x_6, x_7, and x_8 for four other areas. A variable y_2 obtained from this latter graph (not shown here) was combined with the variable y_1 obtained from Figure 14 by a multiple graphical correlation procedure described elsewhere [BRIER, 1946]. The final scatter diagram, Figure 15, shows a greater separation between the two groups than is shown on Figure 14. The slanting lines drawn on Figure 15 (showing roughly the relative frequency of occurrence of Octobers in each part of the chart) were used to assign an index to each month according to where the point fell on the chart. Thus for an October chart the index assigned would be called E since it is related to the earlier month. For a September chart the index assigned would be L since the particular September chart is being

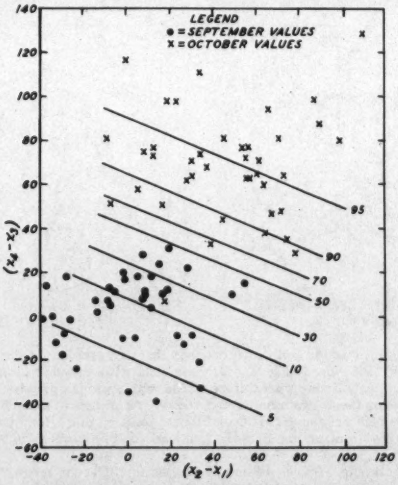

Fig. 14--Scatter diagram showing the separation between monthly mean maps for September and October as a function of x_1, x_2, x_3, and x_4; slanting lines are indices of resemblance to October normal charts

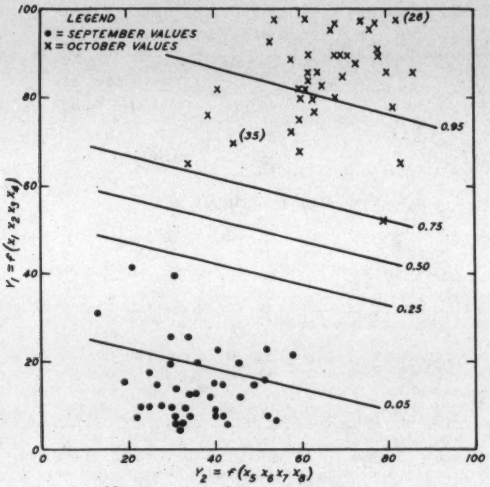

Fig. 15--Separation of September and October maps as a function of y_1 and y_2

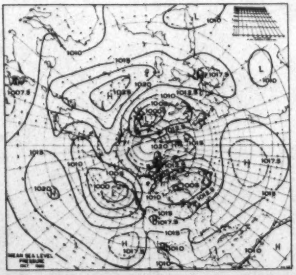

Fig. 16--Mean sea-level pressure map for October 1926

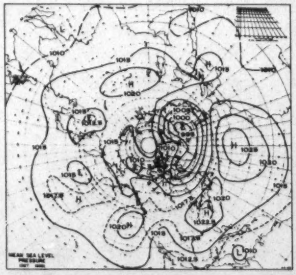

Fig. 17--Mean sea-level pressure map for October 1935

indexed relative to October. For example, two crosses that are labeled on the Figure are for October 1926 and October 1935, indicating that October 1935 with an index of approximately 82 was much more like a September map than October 1926 with an index greater than 95. The mean sea-level pressure maps for these two months are shown in Figures 16 and 17. It will be noticed that October 1926 has the high pressure cell over Siberia built up more than the map for October 1935 and that in addition the Aleutian low is more pronounced for October 1926.

Scatter diagrams similar to Figures 14 and 15 (but using different areas) were prepared for each consecutive pair of months, January-February, February-March, and so on. In nearly all cases it was possible to select pressure indices from areas that gave results similar to that shown in Figure 15. The poorest separation was obtained in the three winter months, December, January, and February. Thus in spite of the variations from year to year, it appears that the circulation pattern for a particular month has some rather definite characteristics which dis-

tinguish it from the adjacent months.

As suggested previously it was thought that the indices expressing the tendency of a particular month to be more like the normal for the previous or subsequent month might show some interesting persistence, trends, or relations to sunspot activity. However, the results of a statistical analysis of these indices were rather disappointing. It was found, for example, that there was very little or no persistence in these indices, so that if a particular monthly mean pattern for September indicated a tendency toward an October type, the following October monthly mean map would be a September type just as often as it would be a November type. However, further studies now being carried out using a slightly different scheme of indexing the monthly mean maps show some interesting statistical relationships. These will be reported upon at a later date.

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RELATIONSHIPS BETWEEN LARGE-SCALE ATMOSPHERIC FLOW PATTERNS AND HAWAIIAN PRECIPITATION

Samuel B. Solot and William H. Haggard

(Sponsored jointly by the Pineapple Research Institute of Hawaii, the Hawaiian Sugar Planters Association, and the United States Weather Bureau.)

Abstract--An attempt is made to relate Hawaiian precipitation patterns to atmospheric flow patterns. Variations in rainfall are produced by changes in the large-scale circulation patterns, modified by local topographic features of the Islands. Examples of circulation patterns and their associated rainfall are presented. Methods of interpreting mean monthly pressure-anomaly charts for the Pacific Ocean area in terms of monthly Hawaiian precipitation patterns are discussed.

In the investigation of Hawaiian precipitation problems, one phase of the research is aimed at the development of a system of monthly precipitation forecasts. An effort has been made to work out the details of a system of forecasting which could be readily fitted into the operational routine of the Extended Forecast Section of the United States Weather Bureau. The preparation of these forecasts consists of two distinct steps [NAMIAS, 1947]: (1) The construction of mean prognostic charts; and (2) the interpretation of these in terms of weather. The first step is a general problem of utmost complexity, in the solution of which the specialized knowledge and experience of many years are utilized by the staff of the Extended Forecast Section. It was decided that the primary objective of the research should be the solution of the second step of the forecast procedure.

In the early stages [SOLOT, 1948] it was found that months of outstandingly light or heavy rain for the entire island area are associated with distinct sea-level pressure-anomaly patterns over the Pacific Ocean area. Although it would be most desirable to extend the analysis to the upper air, the fact that adequate data are practically non-existent made it necessary to resort to sea-level data. Fortunately the large-scale systems in the eastern Pacific are composed principally of warm highs and cold lows and presumably the mean sea-level patterns reflect to a considerable extent the upper-air patterns. In months of general light rain the anomaly chart shows a deficit of pressure in the Aleutian area and a positive anomaly center near the Hawaiian Islands, with above normal westerly flow indicated for the ocean area to the north. The reverse of this pattern is associated with heavy rainfall. Further investigation has shown, however, that this simple concept is not adequate. There are periods during which rainfall for all parts of the territory appears well correlated and the above relationships may be useful in forecasting, but at other times a single precipitation index is not representative for all stations, and a more localized approach is necessary.

It was found necessary to group the precipitation data by homogeneous regions. After considerable experimentation it was discovered that rainfall patterns varied principally by aspect, that is, windward or leeward with respect to the prevailing northeast trade winds, and latitudinally by islands. Composite pressure and pressure-anomaly charts were computed for outstanding cases of light and heavy rain for each homogeneous rainfall grouping. It was found that for any particular homogeneous area the composite anomaly charts for light and heavy rain tended to be exact opposites of one another. Twenty-four separate composite charts were constructed. A complete description of the objective techniques used for sampling the rainfall data and computing the representative flow charts will be found in a forthcoming paper [SOLOT, in preparation].

The pressure-anomaly charts proved more useful than the pressure patterns themselves for long-range forecasting of rainfall anomalies and are discussed in a later section of this paper. Since pressure charts may be interpreted more easily in terms of weather, some examples of these are presented to illustrate the physical processes involved in the production of various rainfall patterns. Before discussing these examples a few general remarks will be made.

Those daily circulation patterns of the winter half of the year, which are not markedly anomalous, consist primarily of a subtropical ridge over the eastern Pacific with a polar low to the

north and west. Rainfall stratifications are extremely sensitive to latitudinal fluctuations of these patterns, which cause variations in the winds over the Islands. These may range from strong easterlies to strong westerlies through weak easterlies, calm, and weak westerlies.

It is evident that easterly circulations produce heavier rain on the eastern slopes of the barriers, while westerly circulations lead to heavier rains on the western slopes. This is the primary basis of the stratification of rainfall by aspect.

In the absence of easterly wave activity with the subtropical-ridge line displaced northward (see Fig. 1) upslope winds produce heavy rain on the eastern slopes of all the islands, while moderately light rain is experienced on the western slopes in the areas of descending currents. With straight or anticyclonic wind flow and pronounced trade wind inversion the rainfall is primarily orographic and strong stratification by aspect is found in the rainfall distribution.

If this type of circulation becomes perturbed and easterly waves are generated, heavy rain on the eastern slopes will be experienced with the northeasterly winds ahead of the wave. As the wave progresses westward, southerly winds behind it will produce precipitation on the southern and western slopes of the Islands, frequently heavy at the southern end of the island chain where the wave activity is most intense. This leads to a northward rainfall gradient.

When the ridge line is somewhat farther south the velocity of the easterlies at the latitude of the Islands is less. Moderate orographic rainfall on the eastern slopes is then contrasted with light rains on the western sides of the Islands, of a purely orographic nature produced by westerly afternoon sea breezes [LEOPOLD, 1948].

If the ridge is located just north of the Islands, weak easterly winds with a latitudinal shear will prevail. Precipitation occurs on the eastern slopes of the southernmost islands, decreasing northward so that the island of Kauai remains relatively dry. If the ridge line is directly over the Hawaiian Islands, however, (see Fig. 2) a condition of general drought prevails with light variable winds and a pronounced inversion aloft. Little or no precipitation falls at any station. This situation may persist for considerable periods of time, with slight fluctuations in the ridge line pro-

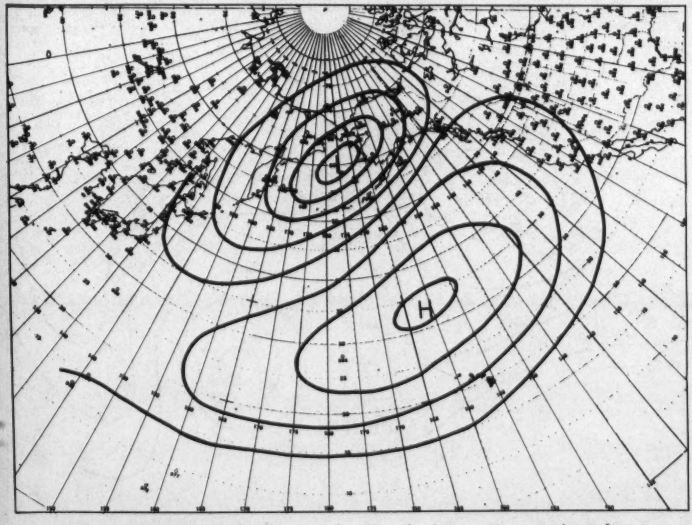

Fig. 1--Composite sea-level pressure pattern for heavy rain on eastern slopes of Hawaiian Islands (strong easterlies) (isobar spacing arbitrary)

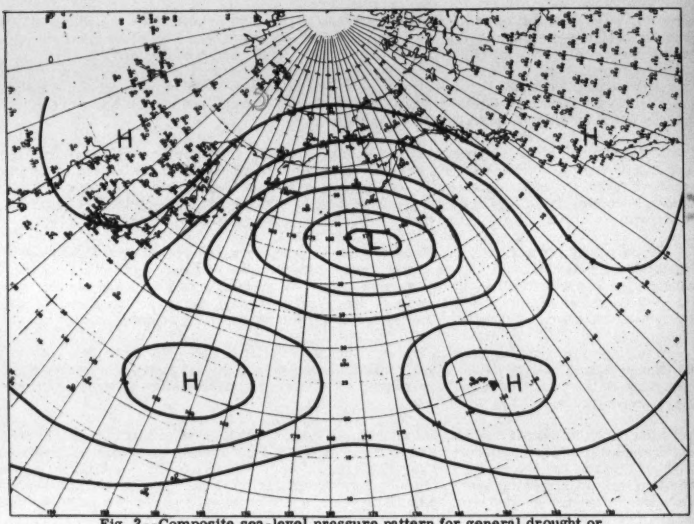

Fig. 2--Composite sea-level pressure pattern for general drought or light rain on Hawaiian Islands (calms) (isobar spacing arbitrary)

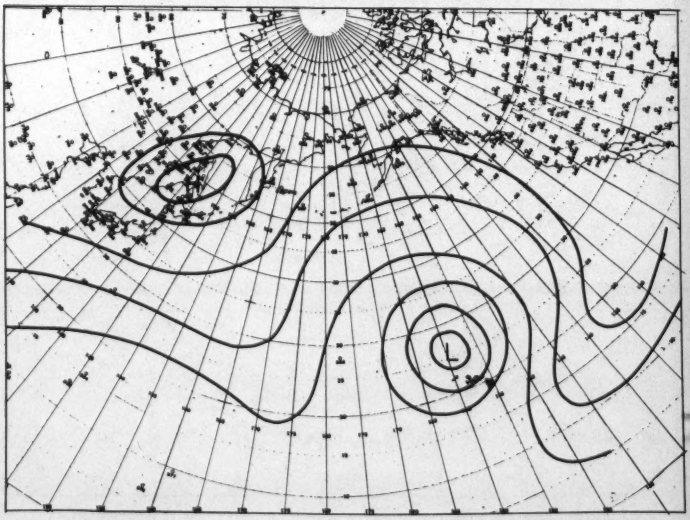

Fig. 3--Composite sea-level pressure pattern for heavy rain on western slopes of Hawaiian Islands (strong westerlies) (isobar spacing arbitrary)

ducing light precipitation stratified northward or southward depending on the location and motion of the anticyclonic cell.

As the polar low is shifted south, upslope winds on the western portions of the Islands produce considerable precipitation. Convergence associated with the cyclonic circulation results in some precipitation in other regions. In general, however, this results in moderate rain on the western slopes and light rain on the eastern sides of the Islands.

When the polar trough is centered just north of Hawaii the Islands are completely within the influence of the westerlies (see Fig. 3). Convergence associated with this cyclonic circulation produces moderate precipitation throughout the territory. When the strong orographic component of the upslope winds is added, extremely heavy precipitation occurs on the western slopes.

These examples of the grosser classifications form a series in which the latitudinal fluctuations of the systems are important. There are, however, some special patterns which do not fit into this series but produce characteristic rainfall patterns. Heavy rain may come about in three ways: (1) Troughs in the westerlies; (2) waves in the easterlies; or (3) a combination of the two which gives the heaviest rains of all (see Fig. 4). This is basically the pattern referred to by RIEHL [in preparation] as universally associated with extremely heavy precipitation in the tropics. He describes it as a polar trough superimposed on a low latitude trough. The circulation aloft is westerly, and it has been suggested that in some cases the easterly trough may actually progress eastward, being steered by the circulation aloft. The blocking ridge to the east, however, is normally so pronounced that both the lower and upper troughs are translated westward.

Though the normal patterns vary greatly with the season, the same types of anomaly patterns are related to the rainfall classes in summer as in winter. In mid-summer the flow is easterly, and the anomaly indicates whether the easterly flow is strengthened or weakened. The absence of westerly circulations at the latitude of the Islands leads to a general minimum of rainfall on the western slopes. In spite of the increased stability, the strong easterlies produce sufficient orographic rain to give a secondary summertime maximum of rainfall on the eastern slopes (see Fig. 5).

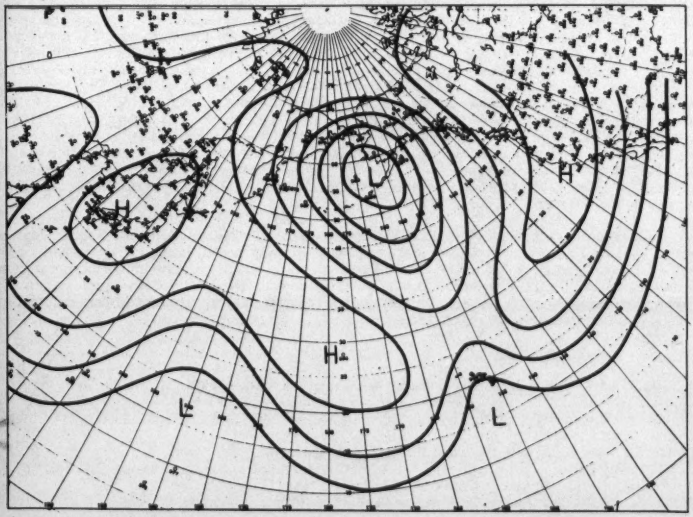

Fig. 4--Composite sea-level pressure pattern associated with general heavy rain on the Hawaiian Islands (isobar spacing arbitrary)

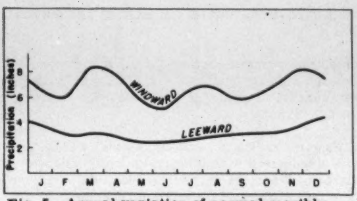

Fig. 5--Annual variation of normal monthly rainfall for stations grouped according to location on eastern (windward) and western (leeward) slopes of Hawaiian Islands (adjusted to 30-day month)

Mean monthly sea-level pressure-anomaly charts are the primary tools of the forecasting procedures. It is therefore important to know how the mean patterns are made up of their individual daily components. The mean pressure-anomaly chart may be composed of an infinite variety of individual patterns. A pronounced mean monthly anomaly pattern may result from: (1) A very persistent situation lasting the greater part of the month; (2) a series of similar recurrent situations; or (3) a single situation lasting only a few days in an otherwise normal month, but in which the pressures depart so far from normal that the pattern is impressed on the mean chart. In regions of migratory systems, such as the United States, the recurrent situation may often be the most important for the production of mean monthly anomalies. Examination of a large number of cases of mean monthly anomaly charts related to Hawaiian precipitation, however, leads to the conclusion that, while the first process occurs occasionally, and the second is quite frequent for months of light precipitation, the third process is the most frequent in months of heavy rain in the winter half of the year. Studies of the rain itself [RIEHL, in preparation] lead to the same inference.

It has been found that the pattern of the anomaly has greater significance in interpretation than does the gradient, and in the construction of the set of twenty-four idealized mean monthly sea-level pressure-anomaly patterns for the Pacific Ocean area which form the basis of the forecast interpretation system employed at present the gradients were equalized to emphasize the pattern.

After the prognostic anomaly chart is completed by the Extended Forecast Section, precipitation forecasts are prepared by determining which of the idealized patterns it most closely resembles. In cases where features of different patterns are evident these must be combined into a consistent forecast. A comparison of the prognostic with individual monthly charts affords a basis for further interpretation. A set of mean monthly sea-level pressure-anomaly charts has been constructed from Northern Hemisphere historical data and is used for this purpose. The observed anomaly chart for January 1948 provides an example of a mixed pattern (see Fig. 6). With the exception of the small low anomaly center north of the Islands, this pattern is predominately that of general heavy rain shown at the top of the Figure. The ideal pattern which has a low anomaly center in this position is that for light rain at stations on the eastern (windward) slopes of Hawaii. This idealized light rain pattern is shown at the center of the Figure. If this pattern is greatly weakened, the observed chart may be considered a combination of the weakened east Hawaii light and the general heavy rain patterns. An interpretation of the rainfall associated with this combination of patterns would be for heavy rain everywhere except on eastern Hawaii where moderate rain is suggested. This interpretation is shown by the upper chart of Figure 7, while the lower chart represents the observed rainfall distribution.

A number of forecasts in which this technique is used have been made on an experimental basis. The results seem to show that more confidence may be placed in the forecast when the particular pattern closely resembles an ideal pattern, while some difficulties are encountered in the interpretation of mixed patterns. It is evident that more information about the manner in which individual patterns combine to form means is required. There are indications also that the rainfall classifications need further refinement.

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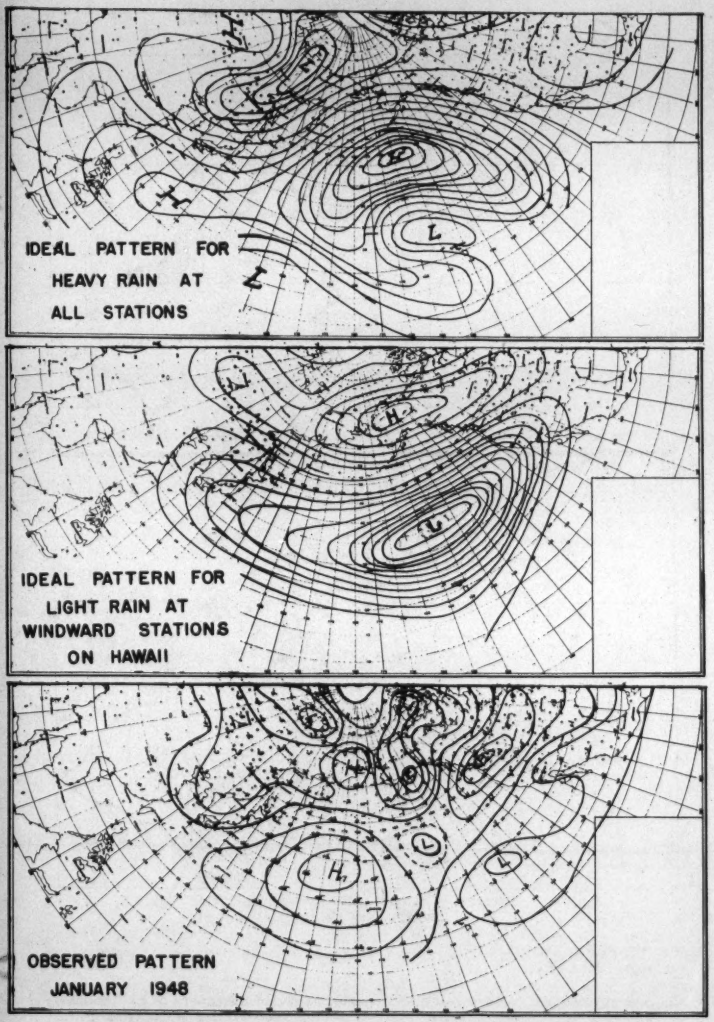

Fig. 6--Composite mean monthly pressure-anomaly charts for general heavy rain (upper), light rain on eastern slopes of Hawaii (center), and observed pattern for January 1948 (lower) (isobar spacing arbitrary)

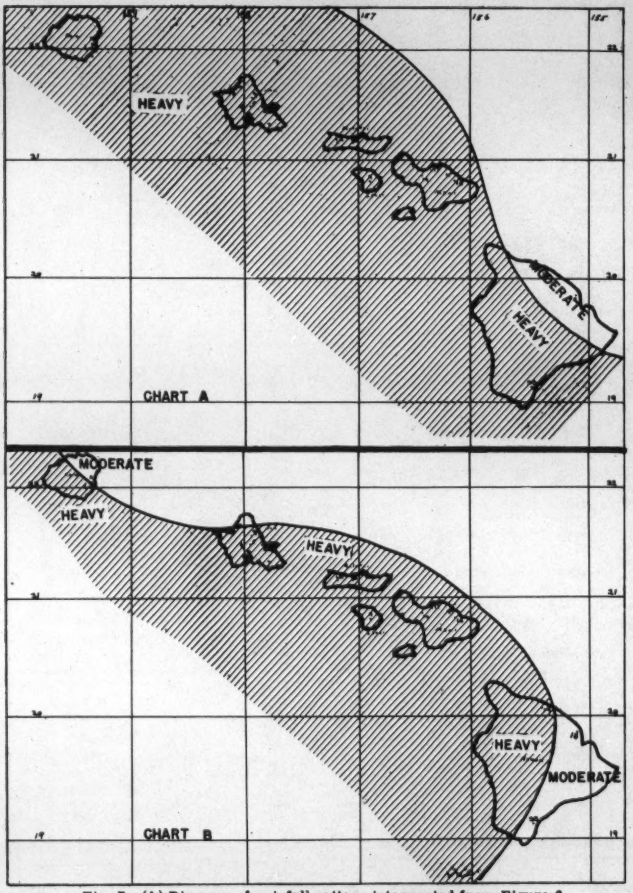

Fig. 7--(A) Diagram of rainfall pattern interpreted from Figure 6 and (B) observed January 1948 rainfall pattern

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PATTERNS OF WORLD WEATHER CHANGES

H. C. Willett

Abstract--Statistical studies of the irregular week to week fluctuations of the general circulation pattern of the Northern Hemisphere indicate the reality of large-scale changes and inter-relationships between the branches of the general circulation of the sort which conform to the ideal high and low index patterns as defined by the strength of the zonal westerlies. On the other hand, lag correlations of these indices fail to establish any significant lag relationships between the branches of the general circulation of the sort that might be expected if these large-scale changes are controlled by some internal mechanism of operation. This result is particularly discouraging for the possibility of statistical long-range forecasting.

The question is raised as to what extent this failure to detect cause and effect relationships in the major changes of the general circulation pattern may be due to inadequacies in the observational data or in the technique of statistical analysis, or to what extent it may be due to the operation of independent external factors of control, such as irregular solar variability.

This possibility of direct solar influence on the short-period irregular changes of the general circulation pattern is further suggested by the marked similarity in pattern of the long-period changes of the general circulation, and the strong evidence which exists for the direct role of irregular solar variability of the sunspot type in these latter changes. Suggestions are offered as to further investigations which might throw additional light on the question as to what extent external (solar) influences may be the primary cause of large-scale changes of the general circulation.

The purpose of this paper is primarily to present a few indicated (or only partially established) statistical and synoptic facts of observation about the general circulation of the Earth's atmosphere. No attempt will be made to establish or demonstrate these facts conclusively at the present time. It is intended further to draw from these hypotheses a few tentative conclusions about the probable operation of the general circulation system, and to indicate certain points at which further study is or should be planned to prove or disprove these tentative conclusions.

The first set of statistically indicated facts of observation deals with the characteristics of the general circulation of the Northern Hemisphere as observed in five-day mean pressure patterns and expressed by contemporary correlations between various circulation indices. It should be noted that the data from which these relationships are established include only 42 months, the winter half-year, October to March, inclusive, of the seven-year period, 1932-1939. Emphasis is placed primarily on the contrast between high and low index patterns, as defined, respectively, by strong or weak values of the zonal westerly indices.

A few words are needed at this point by way of introduction to the statistical investigations which are referred to briefly in the following pages, investigations which were carried out as part of the joint United States Weather Bureau - Massachusetts Institute of Technology extended forecasting project. In this statistical study five-day mean Northern Hemisphere pressure maps at sea level and at the 10,000-foot level (two maps per week at each level overlapping two days on one side and one day on the other) were analyzed for the seven selected winter half-years indicated above. The state of the general circulation for each five-day period was expressed in terms of certain selected circulation indices which were computed from the corresponding five-day mean maps in the case of the zonal indices, and from the five daily maps for the meridional indices.

The zonal indices are of two types, those expressing the strength of the five-day mean geostrophic zonal (east-west) wind velocity between two fixed latitudes, and those expressing the central latitude and the mean geostrophic strength of the zonal wind system in the 20° latitude zone of maximum strength. Thus the fixed latitude zonal westerlies, both at sea level and at the 10,000-foot level, are computed as the mean geostrophic west (positive) or east (negative) wind velocity between 35° and 55°N. The polar easterlies are computed between 70° and 55° (east wind positive) and the sub-tropical easterlies between 35° and 20°. In each case the corresponding maximum zonal wind index is computed between the 20° of latitude for which the pressure difference is observed to be a maximum, and the mid-point of the 20° zone is taken as the latitude of that zonal index. The terms high and low index refer, respectively, to five-day mean maps

with strong or weak zonal westerlies.

The solenoid index (poleward gradient of mean virtual temperature between sea level and 10,000 feet) is computed from the mean sea level and 10,000-foot poleward pressure gradients in the 20° of latitude in which the difference between these two poleward pressure gradients is at its maximum. Thus, it is a measure of the mean thermal wind at 10,000 feet between these latitudes.

The meridional index at any selected latitude and elevation (computed at sea level at 30°, 45° and 70° N, and at 10,000 feet at 30°, 45° and 60° N) expresses the mean north-south component of the geostrophic wind averaged around the latitude circle. It is obtained from the daily synoptic charts and averaged for the five-day period. In computing this index, east-west pressure gradients are averaged regardless of sign, for their algebraic sum around a latitude circle must be zero.

To establish contemporary or lag relationships between the branches of the general circulation as expressed by their respective indices, linear correlation coefficients are computed between the 52 overlapping five-day mean indices for each winter season, and averaged for the seven seasons. In estimating the significance of individual coefficients, it was considered that the 52 overlapping pairs of values should be treated as 26 independent pairs, that is, individual five-day mean index values taken at full week intervals were considered to be independent. The terms significant and highly significant are applied to coefficients which had, on the basis of 26 independent pairs, less than a five per cent and one per cent probability, respectively, of occurring by chance. For the averages of seven seasonal coefficients, the term significant was usually applied to numerical values greater than $\pm$ 0.30, which is well above the one per cent level of significance. The numerical value of the seven season average correlation, as well as the uniformity of the sign of the individual seasonal correlations, is usually stated in cases where significance is attributed to the relationship.

The most noteworthy facts indicated by contemporary correlation are the following:

Pressure correlations

The maximum negative correlation between the weekly changes of the mean pressure on certain selected latitude circles is found between 70° and 35° (correlation -0.54). This fact indicates that the primary tendency for the latitudinal shift of mass of atmosphere is between the subtropical high pressure belt and the polar anti-cyclone, exactly in the sense of the contrast between the typical high and low index patterns. This opposition of variation of the polar and the subtropical highs must operate against positive correlation of the sea-level zonal westerlies and polar easterlies, in contrast to the positive correlation between these two indices which must result from pressure changes in their common boundary zone at about 55°.

Correlations between zonal indices

Sea-level zonal westerlies and polar easterlies--These two indices are found to correlate quite insignificantly (average of seven seasonal coefficients +0.09), probably for the reason indicated above.

Three-km zonal westerlies and sea-level polar easterlies--Surprisingly enough this correlation is found to be uniformly and significantly positive (average of seven seasonal coefficients +0.38). In view of the lack of correlation with the sea-level zonal westerlies, this fact can indicate only that the poleward temperature gradient tends to vary inversely as the sea-level zonal westerlies, that is, that the low index pattern tends to be accompanied by a large thermal wind contribution to the three-km zonal westerlies. This interpretation is confirmed by:

Poleward gradient of mean virtual temperature (solenoid index) and the zonal westerlies--This correlation is consistently and rather significantly negative (average value -0.32) for the sea-level zonal westerlies, and consistently and rather significantly positive (average value +0.34) for the three-km zonal westerlies. This confirms the fact indicated above that the poleward temperature gradient, or thermal wind contribution to the three-km zonal westerlies, tends to vary in opposition to the sea-level zonal westerlies, that is, to be greater with the lower index pattern.

The strength of the three-km zonal westerlies with their own latitude--This correlation is consistently, but not significantly, negative. In view of angular momentum considerations and the increased extent of a latitude zone with decreased latitude, it is rather surprising that this correlation should not be positive. It suggests a tendency for the zonal westerlies aloft to be more

strongly driven as they are displaced southward, a fact which is in agreement with Rossby's explanation of the drive of the zonal westerlies at upper level by the exchange of absolute vorticity.

Correlations between meridional and zonal indices

Meridional exchange at 45° (M I 45) and the strength of the zonal westerlies--This correlation is consistently, but not very significantly, negative both at sea level (average value -0.30) and at the three-km level (average value -0.18, one of seven coefficients positive). This correlation indicates that the usually accepted tendency of the sea-level low index pressure pattern to be meridional (cellular) in character becomes less pronounced with increasing elevation as the zonal westerlies become relatively stronger, due to the strong thermal wind component.

Meridional exchange at 45° and the latitude of the zonal westerlies--The correlation between M I 45 and the latitude of the sea-level zonal westerlies averages exactly zero for the seven seasons, but that between M I 45 and the latitude of the three-km zonal westerlies is consistently and significantly negative (average value -0.35). Thus, the meridional circulation tends to become stronger as the zonal westerlies aloft are displaced equatorward. This fact is consistent with that noted above that the low index pattern is one in which the zonal westerlies tend to be displaced equatorward at upper levels.

Discussion of contemporary correlations

There are two facts of primary significance for this discussion to be noted concerning the above contemporary correlations. The first fact is that although the correlation coefficients are not as high as might be desired, nevertheless they have a certain consistent uniformity which makes synoptic sense in terms of consistent high and low index patterns of the general circulation. In view of the incompleteness of the available synoptic data, the crudeness of the linear correlation technique for the expression of statistical relationships, and the interference which is offered by the continent of Asia to any uniformity of the zonal circulation patterns, it is perhaps surprising that the coefficients are not lower.

The second fact to be noted is that the three-km zonal westerlies show more significant and consistent variation relative to the index pattern than do the sea-level zonal westerlies. It appears from the above correlations that the low index circulation pattern, in contrast to the high index pattern, is characterized by:

(1) A relatively strong poleward temperature gradient, at least between sea level and the three-km level.

(2) Relatively weak zonal westerlies at sea level which increase to relatively strong aloft with a tendency to be displaced equatorward, that is, an intensified and expanded circumpolar vortex in the upper troposphere.

(3) Strong polar easterlies as a result of a relatively strong sea-level polar anticyclone, which in turn is produced primarily from a weakening of the sub-tropical high pressure belt.

(4) In middle latitudes a relatively strong meridional circulation at sea level which tends to weaken with height as the zonal westerlies become relatively stronger.

Lag correlations

The second set of statistically indicated facts of observation about the general circulation of the Northern Hemisphere deals with its characteristics as observed in five-day mean pressure patterns and expressed by lag correlations between the circulation indices. In view of the fact that the large-scale changes of the general circulation between marked high and low index patterns are observed to progress rather slowly from one extreme to the opposite over a period which usually varies from 1 1/2 to three or four weeks, it seems logical to expect that if there is any internal mechanism of operation of the general circulation, such that the subsequent large-scale state is dynamically or thermodynamically determined by the preceding state, then there should exist some significant lag correlation between the circulation indices. The subsequent state as expressed by various circulation indices should have some consistent reflection in the preceding state, as expressed by different values of the indices.

Unfortunately lag correlations between the indices fail to detect any such significant lag correlation over periods of from one to three weeks. Only in cases where there is high contemporary

correlation a reasonable amount of persistence is usually found for one week, but otherwise there is no consistent and significant lag correlation between the selected indices. This fact is very discouraging as regards the possibility of developing a statistical basis for extended weather forecasting. It should be noted that the seasonal trend is eliminated from these index data by plotting the seven-year average of each successive five-day value of each index through the six-month season, and taking the smoothed curve drawn through the successive mean five-day values as representing the normal seasonal trend of the index (strictly it is the normal seasonal trend only as defined by these seven seasons). For index correlation with trend removed, then, departures of the individual index values from the normal seasonal values are correlated instead of the index values themselves. This removal of seasonal trend eliminates considerable positive correlation that results from similarity of seasonal variation rather than from similarity of the irregular fluctuations of the indices.

Discussion of lag correlations

There are three obvious interpretations which may be placed on this failure of any consistently significant lag correlation to appear, namely:

(1) It may be attributed to the crudeness of the statistical technique, that is, either the failure of the selected indices to express the most significant features of the general circulation, or the inadequacy of linear correlation to express completely cause and effect relationships. However, in view of the consistent and synoptically reasonable contemporary correlation which was found, it seems unlikely that any really significant lag correlation could be completely suppressed.

(2) It may be attributed to the fact that only one-tenth of the total atmosphere was treated statistically in this analysis, that is, from 20°N-90°N, between sea level and the three-km level. Even in this zone the observational data are by no means uniformly complete and reliable. Furthermore, this may well be the least significant part of the atmosphere for the initiation of large-scale changes of the general circulation pattern. If such changes do have their origin in the initial dynamic state of the general circulation, they probably originate more frequently in the stronger circumpolar vortex of the Southern Hemisphere, or if the changes are initiated by any direct external (solar) impulse, then they probably appear first in the higher atmosphere and in equatorial latitudes. In either case it seems quite plausible that the initial stages of the change may not be located within the present field of observation.

(3) The final possible interpretation which obviously may be placed on the lack of consistently significant lag correlation between the general circulation indices is to say that there is no internal mechanism of control of the large-scale changes of the general circulation, such that interactions operate over a period of a week or more between the branches of the general circulation. This is tantamount to saying that the subsequent state of the general circulation is not determined by the preceding state, but rather that the large-scale week to week changes of the pattern are induced by some external influence, presumably irregular solar activity.

This third alternative interpretation is certainly contrary to accepted thinking about the behavior of the general circulation of the atmosphere. However, it is not entirely inconsistent with the known facts about the irregular variability of the solar activity which affects the higher atmosphere. Certainly the possibility of such direct external control of major changes of the general circulation should not be arbitrarily ruled out, and should be subjected to any possible verification tests. In the meantime, however, the statistical and synoptic analysis of the circulation changes should be extended to include more of the atmosphere.

Long-period circulation changes

The third set of indicated facts about the general circulation is concerned with the basic characteristics of the very long-period changes of the circulation or climatic patterns. These long-period variations are referred to as secular when a cycle of change or trend is completed within a century (for example, Brückner Cycle), as climatic when the period of change runs through centuries or a few millennia (for example, periods of climatic optimum or of climatic stress since the last ice sheet), and as geological when the period runs into geological time (for example, glacial and inter-glacial ages).

There are two basic facts concerning these very long-period world-wide changes of the general circulation pattern, two facts which are indicated observationally and which, if true, must be considered of primary significance for the explanation of the circulation changes. The first fact has to do with the phase relationship of the circulation changes on the two hemispheres. All of

the evidence, which is notably incomplete particularly for the Southern Hemisphere, indicates that these long-period changes run parallel, or in the same phase, on the two hemispheres. This parallelism seems to be true of the secular changes, notably of the progressive warming and drying from 1880-1940 which reached its peak at the higher latitudes in the 1930-40 decade, with attendant recession of glaciers in nearly all parts of the world. The parallelism is apparently true also, as far as the evidence goes, of the climatic changes, both of the irregular recessions of the last ice sheet, and of the major periods of climatic optimum and of climatic stress since the last ice sheet. Likewise the geological evidence, as far as it goes, points to the parallelism of glacial epochs, and of the successive ice sheets of the Pleistocene epoch, on both hemispheres.

One significance of this parallelism, if it is confirmed by additional evidence, lies in the fact that it eliminates the geometrical variation of insolation, such as that caused by precession or by variation of the eccentricity of the Earth's orbit or of the inclination of the axis of rotation of the Earth to the plane of the ecliptic, from among the possible explanations of the occurrence of glacial and inter-glacial epochs during geological time. This fact would eliminate the Croll-Milankovitch-Zeuner theory of glaciation.

The second significant fact of observation concerning the very long-period changes of the general circulation lies in the essential similarity of the patterns of change to those of the week to week fluctuations between high and low index patterns. Similar latitudinal shifts of the primary zonal characteristics of the general circulation are clearly indicated for the secular changes by the latest (and most completely observed) of BRÜCKNER'S [1890] cyclical changes, by some of TANNEHILL'S [1944] long-period trend curves for the period 1875-1925, especially in western North America, by the northward shift of the sub-tropical high pressure and circumpolar low pressure belts in the 1930-40 decade at the time of maximum warming in the higher latitudes, and by HANZLIK'S [1930, 1931] double sunspot cycle in world pressure patterns.

The major periods of climatic optimum and climatic stress since the last ice sheet are almost identical in character, only much shorter in period and less extreme in amplitude, to the successive ice sheets, or ages, of the Pleistocene epoch. An ice age, like a low index period, apparently is characterized by an expansion of the polar cap circulations, an equatorward displacement of storm tracks and an intensification of storm activity in middle latitudes, a crowding of the sub-tropical high pressure belts towards the equator and a probable intensification of the intertropical convergence and tropical rain belts. An interglacial period, like a high index pattern, is characterized by a contraction of the circumpolar vortex with a displacement of the principal storm activity poleward, an intensification and expansion poleward of the sub-tropical high pressure belts, and probably a marked weakening of intertropical convergence.

The significance of the apparent similarity in pattern of all of the longer-period general circulation changes lies in the implication of similarity of cause or of some common physical control factor for all of these changes. If it is accepted that the secular, climatic and geological changes of the general circulation or climatic patterns are all caused by the same set of control factors, then the very long-period factors like the geometrical variation of insolation or the geological changes such as continental uplift and mountain building are automatically ruled out as primary causes of the longest period climatic changes. There remains by elimination variable solar activity as the most probable primary cause of all climatic fluctuations.

Conclusions

The following tentative conclusions may be drawn from the indicated statistical and synoptic facts of observation concerning the large-scale irregular changes of the general circulation:

(1) There must be definite physical causes operating to produce the long-period irregular changes of the general circulation pattern. These changes occur too consistently, on too large a scale, and over too long periods of time to be the result only of internal dynamic or thermodynamic instability of the circulation patterns.

(2) All of the evidence indicates that these causes operate in the same sense over the whole world, not just over one hemisphere.

(3) The basic similarity of the anomaly patterns of different periods, secular, climatic and geological, suggests definitely that it may be the same set of control factors, operating over different periods and with varying degrees of persistence and intensity, which produces these widely varying cyclical changes of the general circulation pattern.

(4) Variable solar activity, particularly in the shorter ultra-violet wave lengths, such as almost certainly accompanies the sunspot cycle, is the most logical and easily postulated physical control factor which might be made to account for the secular, the climatic and the geological variations of the mean state of the general circulation.

(5) The possibility is by no means excluded that the same highly variable solar factor may be an important influence in the large-scale week to week changes of the general circulation pattern, although if it is, it undoubtedly acts indirectly through the higher atmosphere in a most complex manner. This possibility is suggested both by the failure to find significant lag correlation between the general circulation indices and by the similarity of the five-day mean high and low index patterns to the much longer-period anomalous patterns of the general circulation. Certainly, however, it would not be advisable to accept finally the statistical evidence against significant lag correlation in the general circulation until a greater portion of the Earth's atmosphere has been analyzed over a considerably longer period of time than has been done as yet.

Further study

There are a number of points at which further study is particularly needed, and is either now in progress or being planned, in confirmation or in refutation of these tentative conclusions. The first need is for a more extensive study of general circulation anomaly patterns, more extensive both in time and in space. This can be accomplished in part by the following:

(1) Use of the Northern Hemisphere monthly mean pressure profiles as already computed by the United States Weather Bureau for the historical Northern Hemisphere map series. From these profiles the anomalous variation of the zonal characteristics of the monthly mean circulation patterns can be related to secular weather trends and sunspot activity.

(2) Use of the world-wide monthly mean pressure charts computed by Serra (Brazilian Meteorological Office) for the mid-season months from 1910-1934. Mean pressure profiles can be computed from these maps between 70° N and 60° S, and used to correlate changes of the zonal characteristics of the general circulation on the two hemispheres, and to relate these changes either to secular weather trends or to sunspot activity.

(3) Preparation of current daily Southern Hemisphere charts and five-day mean charts for study in conjunction with the corresponding current Northern Hemisphere charts.

(4) Preparation of world-wide monthly mean anomaly patterns of pressure, temperature and precipitation as related to successive phases of the last ten sunspot cycles (or five double cycles). These charts are to be based on Clayton's World Weather Records, and should make possible a more definite confirmation or refutation than has yet been made of the numerous claims of solar influence on the world weather patterns.

A second need at present is for better indices of solar activity. This requires further investigation and correlation of possible indices of solar activity (such as sunspot numbers or areas), particularly of indices of the intensity of the short-wave ultra-violet radiation from the sun. For this purpose some of the Harvard Observatory coronograph measurements are being tested.

A third need is for further study of the effects, either direct or indirect, of variable solar activity on the Earth's atmosphere. Direct effects certainly can be studied in the ionosphere, and probably also in the ozonosphere. Possible indirect effects on the circulation patterns of the stratosphere should certainly be investigated. Insofar as such effects may be detected in the stratosphere, the effort should be made to correlate them with the much-discussed changes of the general circulation of the troposphere.

Investigations of the type which are listed above should make it possible to answer much more conclusively the principal question raised in this discussion - to what extent are the large-scale changes of the general circulation caused primarily by external influences, or to what extent is the primary cause to be looked for within the Earth-atmosphere system? Certainly this question must be settled before any satisfactory explanation of the mechanics of the general circulation can be offered as a basis for long-range weather forecasts.

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THE PHYSICS OF THUNDERSTORMS

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(Posthumous publication arranged by Richard Van Vliet)

Abstract--The physics of a thunderstorm is studied from the viewpoint of hydromechanics rather than thermodynamics, although the latter processes have not been entirely disregarded. The basic type of thunderstorm herein considered is the case in which the flow phenomena are similar to those existing in connection with two reservoirs with different pressures. The treatment of the various processes involved in a thunderstorm is mainly quantitative. Equations are developed based on the laws of continuity and fluid flow, from which the dimensions and characteristics of a thunderstorm can be determined.

Questions involving the limitation of rainfall splash, maximum limiting rain intensity of the thunderstorm, and the derivation of the characteristics of a thunderstorm, based on study of the rainfall pattern, are considered.

The various hydrological factors involved in a thunderstorm, such as condensation, evaporation, expansion, and lift are discussed.

Introduction and synopsis

A thunderstorm is much like a living organism; it moves, ingests moist air, and produces heat and energy to sustain it, and voids rain and drier air. It has the equivalent of organs which perform specific functions, much like that of the alimentary canal. It preserves its identity as a system while the substance of which it is composed is continually changing. It is born, grows to maximum stature, becomes old and feeble, and dies.

The expression thunderstorm rain is used in the sense of rain produced as a result of strong vertical or nearly vertical convection. The storm usually covers a small area, measured in tens rather than hundreds of sq mi, although, as a result of travel, it may produce rain over a much larger area.

Only one type of thunderstorm is here considered, in which the flow phenomena resemble those through a vertical or inclined pipe connecting two reservoirs with different pressures. This will be called a tubular thunderstorm. A more appropriate title for this paper would perhaps be: The Anatomy and Physiology of Tubular Thunderstorms and the Rains They Produce. The full meaning of this title will, however, be clear only when the paper has been read.

The subject has been treated more from the viewpoint of hydromechanics than thermodynamics, although the latter processes, where involved, are not disregarded. The paper is largely devoted to answering the question: What may be learned about the processes involved in connection with thunderstorms and their rains from meteorological observations taken at the ground level.

The independent variables here involved are barometric pressure, wind speed and direction, humidity, and rainfall, and their changes during the passage of the storm, and, from these observations, simple equations are developed from the law of continuity and the laws of fluid flow, from which the flow conditions in the dimensions of a thunderstorm and the characteristics of the rain which it produces can be determined. The treatment is quantitative and, as far as possible, rational, in that it is based on physical laws and processes.

The most important concepts involved are: (1) The kinematic model of a thunderstorm, subsequently described; (2) the concept of subdivision of moisture condensed in ascending air into two components: (a) The larger drops, which are precipitated on the area over which condensation takes place; (b) drops below a limiting size, dependent on the ascent velocity, which are carried aloft, spread radially in the outflow layer and are precipitated over an area considerably larger, usually several times larger, than the area over which condensation occurs.

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The space containing the ascending air current will be described as the convection tube, and the path of the center of its inlet end as it travels will be called the storm path. If the convection tube is inclined, the path of the center of the outlet of the tube, which governs the distribution of rain, will in general be parallel but not coincident with the storm path. Two principal cases occur: (1) Where the convection tube is vertical or so nearly vertical that its inclination has only an inappreciable effect on rain phenomena; (2) where the convection tube is so inclined to the vertical as to affect the rain phenomena, particularly rain intensity and distribution.

This study is directed toward development of methods for determining maximum station-rain intensity from meteorological data, and basic quantities used in the calculations are those for storms producing maximum or near maximum rain intensities. Fortunately for this purpose limiting values of data required, such as height of ascent, are more readily determined from known data than for other than maximum storms.

The author is indebted to Charles F. Brooks for supplying much needed data, and for two suggestions, made 25 years apart, that have played an important role in the development of the subject: (1) That thunderstorms travel with little regard to surface conditions but more as if they were carried along by an air current at some higher level; (2) That there is a difference between intense convective rains in Rocky Mountain regions and those occurring elsewhere in the United States, resulting partly from smaller increase of wind velocity with height in mountain regions, and partly from greater overheating of the ground surface in semiarid regions.

Characteristics of thunderstorms

The three thunderstorms illustrated by Figures 1 to 3 occurred in widely separated regions, yet the march of the meteorological elements during the passage of the storm over the observation station is very much the same. Another notable characteristic is the close synchronism of the principal changes in the different meteorological elements in the three cases.

It is evident that many well developed or major thunderstorms are similar in appearance and produce similar meteorological phenomena at the ground. The phenomena differ somewhat depending on the position of the observer relative to the center of the storm as it passes overhead. It seems that a typical thunderstorm represents a definite hydrodynamic system and has a definite rheologic or flow pattern, repeated over and over with variation in the elements, much as translatory ocean waves are repeated.

Kinematic model of a thunderstorm--In this study, the model method, often used in physics, has been followed. The kinematic model of a thunderstorm of the type here considered consists of a tube, vertical or inclined, gradually expanding upward to allow for expansion of air in ascent (see Fig. 4). The lower end of the tube is at mid-height of a surface layer of moist air overlain by a cover layer of at least potentially denser, stable air which is pierced by the tube. The tube discharges at a distance below the tropopause and thus constitutes a hydraulic system connecting two reservoirs with different pressures. The tube may be stationary or it may be carried along with the cover layer, while the outflow takes place into air flowing with the same or a different velocity and direction from the motion of the tube. Moist air entering the lower end of the tube has most of its moisture condensed above the condensation level, and in the hail and snow stages this condensation is converted into droplets of various sizes. The ascending air current separates these droplets into the following two components: (1) Large drops, having terminal velocities greater than the vertical component of ascent of air in the convection tube. These fall out as rain on the projected area of condensation. (2) Smaller droplets, which are carried aloft and discharged radially outward into the outflow layer. Drops below a certain size are evaporated and the radius of the outflow layer is such that if such a drop has ascended to the top of the layer and flows outward, falling at the same time with its terminal velocity, it will reach a limiting radius R in the same time required for it to fall through the cover layer. This fixes the maximum limit of the rain spread.

The rain phenomena which will occur in the operation of such a model can readily be determined for given conditions from the law of continuity and simple hydraulic formulas. The necessary data are obtainable from meteorologic observations commonly taken at the ground surface, including temperature, humidity, wind velocity and direction, barometric pressure, and rainfall. The results, computed for specific conditions, particularly as to rain intensity, area of rain splash, and rainfall distribution, can readily be compared with those actually occurring. A thunderstorm which produces results in accordance with the calculated results is designated a tubular thunderstorm. It is shown by comparison of observed and calculated data that most thunderstorms behave in the manner indicated by the model. In this manner the validity of the model is proven

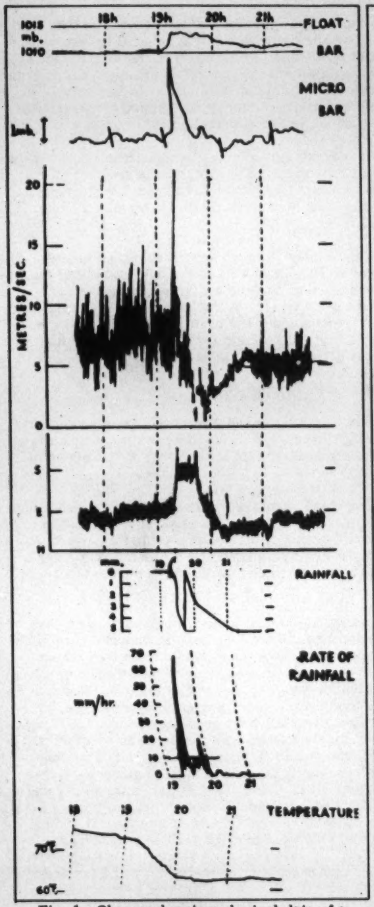

Fig. 1--Observed meteorological data of a thunderstorm

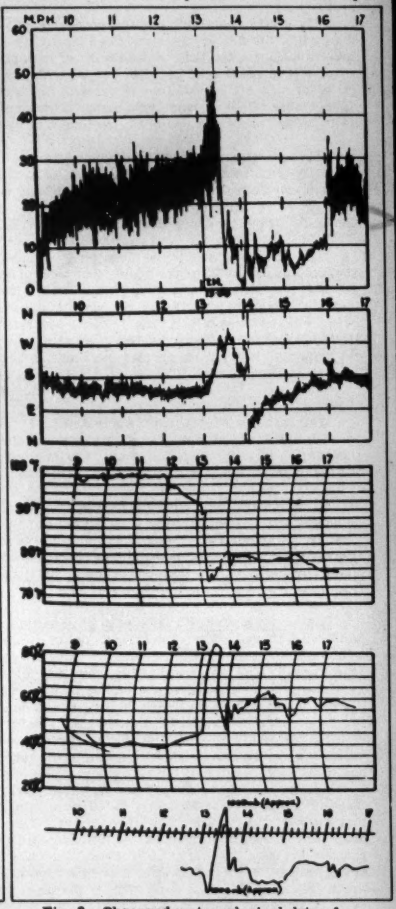

Fig. 2--Observed meteorological data of a thunderstorm

even though it may not accurately represent all the conditions involved. While a convective tube of circular cross section is assumed for purposes of simplicity, the utility of the model is not destroyed if, as is probably often the case, the convective upward current is not of circular cross section. This model reveals the thunderstorm mechanism and its operation stripped of the robe of cloud in which it is ordinarily enveloped.

The conditions favoring strong vertical convection are, as described by SHOWALTER [1944]: It is well known that pronounced rain activity is generally associated with air masses possessing a marked degree of convective instability which, in turn, is generally associated with a lower

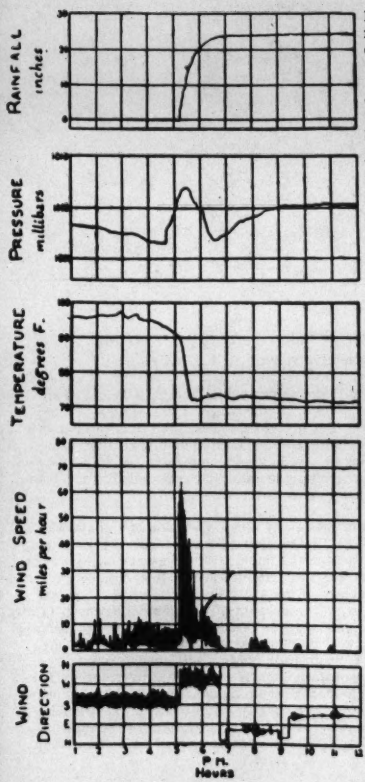

Fig. 3--Observed meteorological data of a thunderstorm

layer of unusually high moisture content separated from a much drier layer above by a stable layer or temperature inversion.

These conditions are provided by the model described. As shown in a separate paper [HORTON, in preparation], the ascending air current in most if not all vertically convective thunderstorms and hailstorms appears to be surrounded by a tubular sheet vortex. This is composed of a chain of ascending vortex rings of moist air forming a sheath around the convection core. Apparently this wall or sheath is thin or absent in intense thunderstorms and thick in hailstorms. It is not shown on Figure 4 since its presence or absence has little effect on the processes involved in thunderstorm rains as distinguished from hail.

The vortex rings composing the sheath are composed of moist surface air and preserve their identity as they ascend. Each ring is surrounded by field circulation which is composed of whatever fluid the vortex ring happens to be passing through at a given moment. This may be moist surface air from the convection core or dry country air from the surrounding region. Most commonly it is a mixture of both.

All conditions may occur from those where the vortex ring sheath is so thin as to be negligible, as in a typical convective thunderstorm with high ascent velocity, to those in which all the ascending moist air is entrained in the vortex rings surrounding the core. In the former case the core of ascending air is moist surface air which may become somewhat diluted with dry air brought in by the field circulation as it ascends. In the latter case the core is dry country air drawn in between successive vortex rings by the field circulation. The lower part of the envelope of cloud surrounding the vortex sheath is a mixture of moist air from the core and country air derived from the field circulation. At higher levels the cloud envelope is probably composed mostly of descending moist air from the outflow layer.

While not important in relation to rain production, certain other features of air circulation in thunderstorms throw light on thunderstorm structure. Acceleration of the downward-flowing air by falling rain at the border of the peripheral outflow ring tends to set up differential motion in the descending air current. At the point where this outflow turns nearly horizontal, at or above the cover layer, the differential velocity may produce violent turbulence or a small vortex. Such a vortex corresponds to the squall cloud often observed at the front of a thunderstorm. As noted by HUMPHREYS [1940], it rotates counterclockwise, the top of the vortex traveling toward the storm. This results from the fact that the downward velocity is greater in the peripheral rain belt near the storm core than at larger radii. The squall cloud lies outside the rain splash, consequently it cannot be a vortex formed by ejection of air at the break in the cover layer. The storm collar [HUMPHREYS, 1940] surrounds the base of the storm at a still greater radius. This is of the same nature but occurs at the outer limit of the down-flow and results from its motion relative to the country air.

That the descending air current surrounding the convection tube can be accelerated by rain falling through it is easily demonstrated. For a given drop size and suspension velocity v_s and with N drops per cubic meter, the falling drops induce an acceleration a' on the surrounding air.

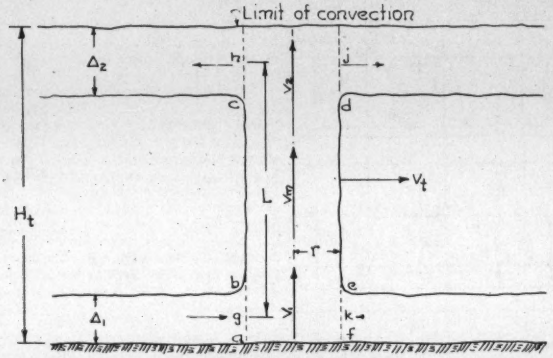

Fig. 4--Ideal convective storm

Since force = mass × acceleration, a′ = (Weight of drops per cubic meter)g/(Weight of air per cubic meter. For example, one two mm drop/dm^3 = 4.19 cm^3 or grams of water/m^3. Dry air at 0°C and 760 mm pressure weighs 1293.05 gr/m^3. For g = 981 cm/sec/sec the acceleration a′ is 3.15 cm/sec/sec. Rain in a descending air current can of course fall at a velocity relative to the Earth greater than its suspension velocity. If falling at a velocity of ten m/sec, the rain intensity would be roundly six in/hr, which is not an unusual rate for the short interval, usually less than 20 min, required for the front peripheral rain to pass over a given point.

Many sketches have been published purporting to represent a cross section of a convective thunderstorm [BLAIR, 1942; ALBRIGHT, 1939; WILLETT, 1944; and BRANCATO, 1942]. These sketches are guardedly indefinite as to the air currents in the interior of the storm, which is concealed by cloud. All such sketches which the author has seen either show or inferentially require the existence of a downward return current in the center of the ascending air stream. The type of flow required to support this theory is unknown in hydromechanics. (The central downward flow is characteristic where the falling rain is heaviest, and is a combination of rain drag and thermal currents.--C. F. Brooks). Apparently it could not exist in the presence of the free opportunity for a return current in the region surrounding the ascending air column with much reduced resistance to flow. It seems probable that the authors of such sketches have been over-influenced by certain physical phenomena, such as the squall cloud, the storm collar, and the apparent outrush of air at the onset of the storm. These phenomena are equally well or better explained by the thunderstorm model of the convective tube type. Probably the explanation of the outrush of air is not as simple as it appears superficially and may be in part the result of field circulation of the vortex ring forming the squall cloud.

In the sketches referred to, the cloud and rain patterns are those of a vertically convective thunderstorm, while the air circulation shown closely resembles that which would occur in a solitary or rolling wave. Probably this circulation does occur in the roll cloud which often accompanies the passage of a cold front. A vertically convective thunderstorm does not produce a long narrow rain splash at right angles to the direction of its travel. Instead it produces a more or less circular rain splash.

Fulks' diagram--The thickness Δ_1 = ab (see Fig. 4) of the inflowing layer of moist air is related to surface dew-point temperature θ_d. A curve showing this relation, as determined by the Hydrometeorological Section, United States Weather Bureau [ANONYMOUS, 1941] is shown on Figure 5.

For purposes of calculation the problem may be treated as if the convective tube extended from the level $\Delta_1/2$ up to h_1 at the center of the outflow layer, and inflow and outflow all occurred at these levels. It is necessary to determine the dew-point temperature at these levels. This and other elements of the computation are most readily carried out by the use of a thermodynamic diagram of the atmosphere. The most complete diagram is that of NEUHOFF [1910]. A simplified diagram which serves present purposes is that of Fulks (see Fig. 6). On this diagram vertical

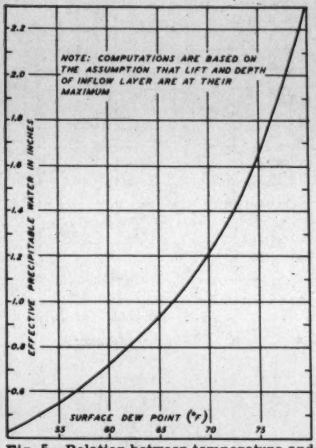

Fig. 5--Relation between temperature and depth of layer of moist air

lines represent temperature, °C; horizontal lines represent pressure, in mb; lines sloping slightly downward from left to right show elevations in km corresponding to different pressures and temperatures; curved lines sloping upward to the left are pseudoadiabats showing temperature and pressure at a given altitude in a mass of rising air saturated at the surface and cooling as it rises at the pseudoadiabatic lapse rate, that is, the rate at which temperature decreases in an ascending mass of saturated air cooled by adiabatic expansion. Curved lines sloping upwardo the right represent rates of condensation in mm/hr in such an ascending air mass, with a vertical depth of 100 m. For example, a mass of saturated air at 20°C, starting at the surface, would follow a course parallel with the adjacent pseudoadiabats and would attain a temperature of 16°C and a pressure of 900 mb at one km elevation, a pressure of 800 mb and a temperature of 11°C at two km elevation, and so on. When the center of this air mass is at two km elevation, it would produce condensation at the rate of approximately 0.7 mm/hr for each m/sec of ascent velocity.

Lift--Maximum condensation rate for a given ascent velocity will occur in conjunction with maximum dew-point temperature and maximum height of ascent of the air column. For purposes of calculation the height of ascent or lift will be taken as the vertical distance from the center of the inflow layer at level gk, Figure 4, to the center of the outflow layer at level hj. Because of expansion in ascent of the air the thickness of the outflow layer Δ_2 is greater than the thickness of the inflow layer Δ_1. (It is assumed here that the speed of outflow at the top is less in proportion to that of inflow at the bottom than the ratio of the densities. It must be borne in mind, however, that with a certain pressure gradient the flow increases in proportion to the decrease in density, which would tend to keep Δ_2 from getting much greater than Δ_1.-- C. F. Brooks) The mass of outflow is the same as the mass of inflow but because of expansion in ascent the diameter and velocity at the top of the convection tube and the thickness of the outflow layer will all, in general, be greater than at the inflow level. In more intense storms the outflowing air contains so little moisture that considerable variation in the assumed height of lift makes relatively little difference in the calculated condensation rate. In intense thunderstorms the tops of cumulo-nimbus clouds often extend nearly to the stratosphere. The extreme top of the cloud contains so little moisture that it may be neglected and maximum condensation may be taken as that occurring with maximum surface dew-point temperature and with the top of the outflow layer at the tropopause, or base of the stratosphere. Table 1 gives values that correspond to conditions in northern and eastern United States [ANONYMOUS, 1941].

Table 1--Cloud heights, tropopause, and freezing level

Item	Summer		Winter	
	ft	km	ft	km
Cumulo nimbus cloud tops				
Maximum elevation	52,000	16	30,000	9.0
Average elevation	16,000	5	11,500	3.5
Average base of stratosphere	43,000	13	33,000	10.0
Average freezing level	20,000	6	10,000	3.0

To simplify computations for maximum conditions the assumption may be made, as has been done by the Hydrometeorological Section of the United States Weather Bureau [ANONYMOUS, 1941] that for a maximum condensation the top of the outflow layer is at the level h_t of the base of the stratosphere and that the height of lift, $L = 2h_t/3$. Then since

$$h_1 = \text{mean inflow level} = \Delta_1/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

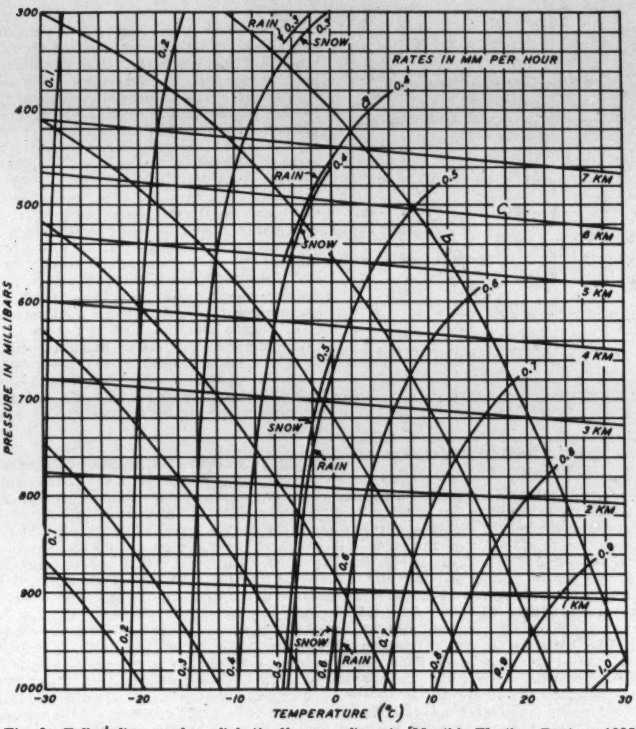

Fig. 6--Fulks' diagram for adiabatically ascending air [Monthly Weather Review, 1935]; a = rate of precipitation, rain or snow, for a 100-m layer with a vertical velocity of one m/sec; b = saturated adiabats; and c = altitude lines

it follows that

$$h_2 = \text{mean outflow level} = \Delta_1/2 + 2h_t/3 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The thickness of the outflow layer is

$$\Delta_2 = 2h_t/3 - \Delta_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Condensation level--For the purpose of determining maximum thunderstorm rain it is assumed that the air is saturated from the ground surface upward to the base of the stratosphere and is at its extreme or limiting maximum dew-point temperature at the ground surface. Ordinarily the surface air just preceding the storm has a temperature somewhat above the maximum dew-point temperature and the condensation level is above the ground surface. The lapse rate is then adiabatic up to the condensation level (1°C per 100 m) and the height of the condensation level in km is

$$h_c = (\theta_0 - \theta_d)/10 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Expansion--A mass of air of diameter $2r_1$ and of unit height at the inlet level, will have a volume $V_1 = \pi r_1^2$. If the expansion ratio is ρ_e, then at outflow level the volume is

$$V_2 = \rho_e V_1$$

or

$$V_2/V_1 = \rho_e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

If expansion takes place equally in all directions the air mass at the upper level will have a radius r_2 such that

$$\left.\begin{aligned} 2r_2 &= 2r_1 \rho_e^{1/3} \\ r_2/r_1 &= \rho_e^{1/3} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

and a height $\rho_e^{1/3}$, so that its volume will be

$$\pi r_1^2 \rho_e$$

The imaginary walls of the convection tube may be considered as extended downward to the surface and upward to the tropopause, as shown by dotted lines on Figure 4. From (6)

$$r_2/r_1 = \rho_e^{1/3}$$

If

$$\Delta_2/\Delta_1 = \rho_e^{1/3}$$

then

$$v_0/v_h = r_1\Delta_1/r_2\Delta_2 = 1.0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The last result shows that if the thickness of the outflow layer is proportional to the vertical component of expansion, then the horizontal velocity of outflow across the walls of the convection tube will be the same as the horizontal velocity of inflow, both taken across the walls of the convection tube extended, and both relative to its rate of travel, not relative to the Earth. Under these conditions the horizontal outflow velocity is not affected by expansion, in other words, the outflow area is increased in the same ratio ρ_e as the volume and consequently the outflow velocity, $v_0 = v_h$. Also

$$V_1 = \pi r_1^2 v_1$$

$$V_2 = \pi r_2^2 v_2 = \rho_e V_1$$

and since

$$(r_2/r_1)^2 = \rho_e^{2/3}$$

$$v_2/v_1 = \rho_e^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Equation (8) shows that the average ascent velocity at the outflow end of the convection tube is greater than at the inflow end in the ratio $\rho_e^{1/3}$. The maximum ascent velocity, other things equal, will occur somewhat below the center of the outflow layer because the ascending air begins to spread at the base of the outflow layer. For practical purposes it is assumed, unless otherwise noted, that the vertical velocity at the center of the outflow layer is sensibly the same as the maximum ascent velocity. The mean ascent velocity will be the integrated average velocity from the inflow to the outflow level. Approximately

$$v_m = (v_1 + v_2)/2 = (1 + \rho_e^{1/3})v_1/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

For $\rho_e = 2.0$ this gives

$$v_m = 1.13\ v_1$$

$$v_1 = 0.885 v_m$$

$$v_2 = 1.12\ v_m$$

$$= 1.27\ v_1$$

From the gas laws, $PV = R_g T_K$, where T_K = absolute temperature, Kelvin; R_g = the gas constant for the system of units used.

Using subscript 0 for ground level or standard conditions,

$$PV/P_0V_0 = T/T_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

and the expansion ratio is

$$\rho_e = (P_0/P)(T/T_0) = (P_0/T_0)(T/P) = R_g T/P \quad \ldots\ldots\ldots\ldots\ldots (11)$$

where

$$R_g = P_0/T_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Using P_0 = 29.9 inches = 759 mm = 1013 mb, and T_0 = 86°F = 30°C = 303°K, which is about maximum dew-point temperature, R_g = 0.09868 or roundly 0.1 for P in inches and temperatures Kelvin.

Using seven km as approximately the base of the outflow layer for maximum storms and taking temperatures and pressures at this level from Fulks' diagram, for ground temperatures as shown in column (1) of Table 2, values of the expansion ratio ρ_e are obtained as shown in column (8).

Table 2--Expansion ratios

θ_d		θ_d		T/T_0	P_{mb}	P_0/P	ρ_e
C	Kelvin	C	Kelvin				
1	2	3	4	5	6	7	8
15	288	-26	247	0.856	412	2.43	2.08
20	293	-16	257	0.877	421	2.38	2.08
25	298	- 6	267	0.896	432	2.32	2.08
30	303	+ 4	277	0.914	442	2.26	2.08

For the assumed conditions the expansion ratio ρ_e comes out so close to the constant value 2.00 that ρ_e = 2.00 may be used without sensible error for conditions usually prevailing in maximum convective storms. It is true that the summits of cumulus clouds are sometimes carried above the tropopause and to some distance into the stratosphere. This apparently results chiefly from their momentum. These extreme summit clouds, however, produce little if any rain above the base of the stratosphere, and the conditions assumed suffice for present purposes.

Condensation rate--Before taking up flow phenomena in the outflow layer it is necessary to give some consideration to condensation rate and its relation to rate of rain production. The terms volumetric condensation, C_r, and volumetric rain intensity, V_p, will be used to describe, respectively, the total amount of condensation per unit of time in the convection tube and the total volume of rain precipitated on the rain splash area per unit of time.

Condensation rate is a function of two factors: Vapor content of ascending air, and rate of ascent. The volume of air entering the base of the convective cylinder bcdo (see Fig. 4) is $V_1 = \pi r_1^2 v_1$. At maximum height, $v_m = \pi r_m^2 v_m$. At outflow, $V_2 = \pi r_2^2 v_2$. The differences of volume resulting from expansion are reflected in the values of r and v.

Each unit of volume contains a mass of vapor m1 equivalent to an equal volume of liquid water in cubic centimeters. The air is cooled as it rises and expands, but the mass of air leaving the tbp cd of the column, exclusive of water vapor, is the same as that entering the base. Because of

the lower temperature resulting from expansion, the vapor content m_1 per unit of mass or per unit of original volume, is reduced in ascent to m_2.

If $m_c = m_1 - m_2$ the mass in grams or the volume in cc of vapor condensed out of one cubic meter of air at this temperature and pressure at entrance to the convection tube will be

$$C_r = \pi r_1^2 v_1 m_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

For $\rho_e = 2.00$, $r_m = 1.13 r_1$ and $v_m = 1.13 v_1$. This gives

$$\left.\begin{aligned} C_r &= (1/1.13)^3 \pi r_m^2 v_m m_c \\ &= 0.693 \quad \pi r_m^2 v_m m_c \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

If m_c is in gr/m^3 and r and v in m and m/sec, then C_r will be in cm^3/sec.

Expressed in depth on the projected mean cross-section area of the convection tube

$$\left.\begin{aligned} c_r &= 0.693 \; v_m m_c / 1000 \text{ mm/sec} \\ &= 0.10 \quad v_m m_c \text{ in/hr} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

This is 1/10 in/hr of condensation per gr per m^3 of condensible vapor in the original area, and per m per sec of mean velocity of ascent.

If there were no intermediate loss of water, then the volumetric precipitation rate would be $V_p = C_r$. There are, however, intermediate losses.

Storage and dissipation of vapor by clouds--If a given volume of water is condensed from an ascending air current, then the volume available to produce rain is reduced by the volume which is entrained and later dissipated as water droplets in cloud. It is commonly assumed that this is negligibly small. However, under conditions existing in a violent thunderstorm this may not be the case.

Let V_1 = volume of water in cloud droplets, cc/m^3. The equivalent depth in mm is $1000 h V_1/10{,}000$ for h in km.

Using WEGENER'S [1940] measurements of water content of clouds in the Swiss Alps, V_1 = 0.35 to 4.8 gr/m^3. For an average value of $V_1 = 2.50$ gr/m^3, $d_2 = 0.25$ cc/km = 2.5 mm/km. For a cloud column 10 km in height this is equivalent to 25 mm or one inch depth of water. Results of the same order are obtained using Humphreys figure of 120 cloud droplets, 33 microns in diameter per cm^3 of dense cloud [HUMPHREY, 1940]. This gives 21.6 mm or 0.84 inch of water equivalent in a 10-km cloud column.

The cloud mass in a convective cumulus cloud may be considered as a cylinder ten km in height and ten km base diameter. Such a cloud mass would contain roundly 785 km^3, and with 2.5 cc cloud droplets per m^3 the total volume of water contained in cloud droplets would be 1962×10^9 cc total (1 m^3 = 10^6 cc). This is equivalent to 1,962,000 m^3. This enormous quantity of water may become inactive as cloud. In the example given this water would be distributed over an area 78.5 km^2 and would be equivalent to a depth of 2.5 cm.

During early stages of a convective storm, the accumulation of moisture storage as cloud continues at such a rate that condensation rate minus drop formation rate equals rate of accretion to cloud storage. Meanwhile evaporation takes place from the increasingly larger exposed cloud surface. Equilibrium is attained when, for a steady storm, rate of accretion to cloud equals evaporation loss from cloud surface. Previous to this time, that is, in the early stages of the storm, the volumetric precipitation may be and usually is much less than the volumetric condensation rate. After the steady state is attained, a constant volume of cloud storage is carried forward with the storm and finally dissipated when the storm subsides. This volume of cloud is in effect abstracted from condensation in the early stages of the storm and, after equilibrium is attained, cloud storage has no further direct effect on the precipitation rate.

Evaporation--After cloud storage becomes filled, precipitation takes place, barring minor variations from gustiness, at a rate equal to the condensation rate, excepting for loss by evaporation.

The rate of evaporation from a cloud surface at high altitude is unknown and involves several factors: Low temperature, effect of wind, and rate of evaporation from drops as compared with that from a plane surface. Evaporation from a standard Class A, United States Weather Bureau pan rarely exceeds 0.02 in/hr as a maximum. Evaporation from small droplets may take place at much higher rates per unit of surface, as has been shown theoretically and experimentally. The evaporation from cloud surface may conceivably equal and perhaps exceed that from a plane surface in a similar environment, but even then, because of the extremely low temperatures, it is doubtful if it is ever as much as 0.01 in/hr depth on the projected rain splash area.

The total surface exposed to evaporation equals (number of droplets per unit of surface) × (surface per drop) × (total cloud surface).

Evaporation occurs not only from the surface layer of cloud droplets but to a small depth within the cloud. For 2.5 gr of cloud droplets per m^3 and 100 droplets per cm^3, with droplets 0.338 mm in diameter, the drop surface is 0.0359 m^2 per m^3 of cloud. If evaporation extends to one m depth and at a rate of one mm per hour, or roundly one inch depth per day, the evaporation would be 0.036 mm per hour on the exposed surface. For a cloud evelope equivalent to a cylinder ten km in diameter and tem km in height, this would be equivalent to 0.144 mm depth per hour on the basal area of the cylinder or roundly 0.1 inch per day. This water is derived from the ascending core of air through the field circulation and is replaced as fast as it is lost. Since it requires usually less than one hour for a rain splash to pass a given point, this loss is relatively small compared with the rain splash intensities commonly occurring in intense convective storms.

Rheology of thunderstorms--The term "rheology" connotes something more than motion or kinematics. It also includes the physical nature of flow processes. While this term has hitherto generally been used chiefly in connection with flow of plastic substances, the extension of its use to the condition here under consideration seems appropriate.

The term country wind, analogous to country rock of the geologist, will be used to describe the prevailing surface wind at a sufficient distance from the storm center to be unaffected by the storm.

Using the thunderstorm model, Figure 4, it will be assumed that the horizontal velocity v_h of flow across the walls of the convection tube at its base is constant all around its circumference. This is the velocity relative to that of the convection tube, not that relative to the Earth.

If there is no country wind at ground level the storm is carried along with the break in the cover layer at a velocity v_t. If the absolute values regardless of directions of the wind velocities at the front and back of the storm at ground level relative to the Earth are $|w_f|$ and $|w_b|$, then for the same velocity v_h of entry around the convection tube,

$$\left.\begin{aligned} |w_f| &= v_t + v_h \\ |w_b| &= v_t - v_h \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Inflow to the convection tube will then continue uniformly around its circumference. Thus there is a strong ground wind at the front directed toward the storm and a weaker ground wind at the back from the opposite direction. If $|w_f|$ and $|w_b|$ are known

$$v_t = |w_f| - v_h = |w_b| + v_h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

From Figure 4

$$\pi r_1^2 v_1 = 2\pi r_1 \Delta_1 v_h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

and

$$v_h = r_1 v_1 / 2\Delta_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

Also

$$\Delta_1 = r_1 v_1 / 2 v_h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

The time $T = t_2 - t_1$ between maximum wind velocities at the onset and end of the storm with respect to an observer in the path of the storm center, is the time required for the storm to travel a distance $2r_1$ or

$$v_t T = 2r_1$$

and

$$\left.\begin{aligned} v_t &= 2r_1/T \\ r_1 &= v_t T/2 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

From (17) and (19)

$$v_h = (w_f - w_b)/2 = r_1 v_1 / 2\Delta_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

or

$$\Delta_1 = r_1 v_1 / (w_f - w_b) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

Δ_1 may also be determined for given conditions from Figure 5 or, if available, from upper air observations.

At the center of the convection tube, v_h becomes zero and if there is no country wind, the measured wind velocity w_c at this point equals v_t, the translational velocity of the convection tube. This value v_t may be used to determine r_1 and Δ_1. This gives

$$r_1 = w_c T/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (24)$$

As shown later there is usually a maximum of smoothed rain intensity with respect to an observer in the path of the axis of the storm at the time the front of the convection tube reaches him. There is a secondary maximum when the back of the tube passes the observer. The difference of these times may be used as the value of T in (21) to determine r_1. Another method is given later. When data permit two or more of these methods to be applied, the average determination or more consistent determinations should be used.

The methods described for determination of r_1 and Δ_1 become unreliable if the ground level observations are not taken in or close to the path of the center of the storm or if there is a country wind. In the latter case the component of the country wind as determined somewhat remote from the storm in the direction of storm travel must be added algebraically to w_c.

Ascent velocity, first method--The preceding analysis provides a means for determining the ascent velocities v_1 and v_2 if, as is assumed, the thickness Δ_1 of the inflow layer is known.

From (19)

$$v_1 = 2\Delta_1 v_h / r_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (25)$$

Assuming that an approximate value of Δ_1 has been obtained, and that w_f, w_b, T, and w_c are known, v_1 can be determined from the equations

$$v_h = (w_f - w_b)/2$$

$$r_1 = w_c T/2 = v_t T/2$$

and

$$v_1 = v_2 = 2\Delta_1 v_h / r_1$$

Ascent velocity, second method--The maximum ascent velocity v_g may be calculated from the height J of the familiar barometric jump, which occurs just at the onset of the storm. BUELL [1943] has given the approximate formula

$$v_g = \sqrt{2R_g (T_s/P_s)J} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (26)$$

where R_g = gas constant, T_s and P_s = surface temperature, Kelvin, and surface pressure, mb; J = height of barometric jump, mb. For T_s = 300°K (80.6°C) and P_s = 1000 mb, this equation can be reduced to the form

$$\left.\begin{aligned} v_g &= (\text{in ft/min}) = 2580\sqrt{J} \\ v_g &= (\text{in ft/ sec}) = \ \ 43\sqrt{J} \\ v_g &= (\text{in m/ sec}) = 13.1\sqrt{J} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (27)$$

The error of the equation for different lapse rates in °C per km at the level of the maximum velocity is given by BUELL [1943] as follows: For fully developed cumulo-nimbus, the conditions usually existing during severe thunderstorms:

Lapse rate (°C) × height of level of maximum velocity (km)	30	35	40	50	60	80
Error, per cent	24	12	7	-7	-13	-23

For well developed cumulus congestus, with the anvil about to form, the errors are negative, ranging from -10 per cent for lapse rate value 30° km to -27° for a value of λ = 80°. The errors are negative, usually -1 to -10 per cent while cumulus congestus is developing. The maximum ascent velocity by Buell's formula should be comparable with v_2, the ascent velocity at the upper end of the convection tube, as given by (25).

Ascent velocity, third method--The thunderstorm model may be considered as a hydraulic system discharging a volume V_1 of air (at initial pressure and temperature) per unit of time from one reservoir to another through a pipe of average radius r_m and length L, with a pressure difference $P_1 - P_2$ between the two reservoirs. If steady flow occurs and the resistance to flow varies as the square of the velocity, then the velocity will vary as the square root of the slope or pressure gradient and

$$v_m = k'\sqrt{P_1 - P_2/L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

The factor k' depends on the radius r_m and the units used. Variation of diameter of the convection tube also affects v_m. This effect may be included in the constant k'. Also,

$$V_1 = a_m v_m = k' a_m \sqrt{P_1 - P_2/L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

For pseudo-abiatic ascent the ascending air is assumed to be in equilibrium with surrounding air. The pressure difference $(P_1 - P_2)$ is the buoyancy of the moist warm surface air below the cover layer. Vapor weighs 0.623 times as much as dry air. The buoyancy of unit volume of moist air overlain by drier air is equivalent to an upward-directed force equal to the difference in weight of the two unit volumes and hence, other things equal, to the difference in vapor pressures, so that $e_1 - e_2$ may be used instead of $m_1 - m_2$. The pressure difference $P_1 - P_2$ also includes the buoyancy (if any) of the surface air resulting from surface overheating. This is proportional to the surface temperature excess above the dew-point temperature, or $P_1 - P_2 = (e_1 - e_2) + k'(\theta - \theta_d)$. The residual vapor pressure e_2 and the second term in this equation are both usually small relative to e_1 for conditions producing maximum storms except in semi-arid regions, and $k'(\theta - \theta_d) - e_2$ may be replaced by a quantity c, which can, as shown later, be determined for a given region from observed maximum rainfall data.

Making $k = k'/\sqrt{L}$ gives

$$v_m = k\sqrt{e_1 + c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

There are various other effects and factors of secondary importance which are thrown into k and c and are taken into account in their determination from observed data.

For steady conditions $C_r = i_s A_s$. If i_s and A_s are known, then C_r can be determined from the rainfall data. Methods for determining i_s and A_s from rainfall are subsequently given. Then, from (14)

$$v_m = C_r/a_m m_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (31)$$

The condensible moisture m_c can be determined from vapor pressure e_1. Combining (30) and (31) gives

$$k = C_r/A_m m_c \sqrt{e_1 + c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (32)$$

This provides a means of determining the coefficient k in the ascent velocity equation (30).

The volumetric condensation rate is, from (14), for $\rho_e = 2.00$

$$C_r = 0.693\ m_c v_m, \text{ in cm}^2/\text{m/sec} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (33)$$

This simple equation is rational in form in the sense that it is based on the equation of continuity and the law of resistance for turbulent flow. It is subject to the limitation that it applies only where the resistance to flow is proportional to the square of the velocity or where the flow is turbulent, as is unquestionably the case in a rapidly ascending air current.

Ascent velocity, fourth and fifth methods--In a storm where there is neither gain nor loss of aerial storage as rain or cloud, the precipitation rate on the rain splash area equals the condensation rate in the convection tube. If $m_c = m_1 - m_2$, is the air mass of vapor condensed out of unit volume of air entering the convection tube, and R is the radius of the rain splash over which rain is falling at a given instant, $\pi r_1^2 m_c v_1 = \pi R^2 i_a$, where i_a is the areal average rain intensity over the rain splash. This gives

$$v_1 = (R/r_1)^2 = i_a/m_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (34)$$

In order to apply the last equation it is necessary to know the radius R of the rain splash. This may be determined, as shown in the subsequent sections, from data of drop sizes and their suspension velocities. Such data also provide an additional method of determining ascent velocity. This method and a comparison of the various methods of determining ascent velocity will be given later.

Terminal or suspension velocity--The terminal or constant velocity attained by a falling raindrop is the same as the ascent velocity of an air current capable of holding the drop in suspension. LAWS [1941] has reviewed various earlier determinations of the size of drops held in suspension by ascending air currents of different velocities and has also given the results of additional field and laboratory experiments. The data from Laws' experiments and outdoor observations in rainstorms are given in the form of a diagram. The results are quite accurately expressed by the following equation

$$d = 5.7 - 1.55\ (v_s)^{0.2} \sqrt{9.3 - v_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (35)$$

In this equation d is in mm and v_s in m/sec. The results are as follows:

v_s	= 2	3	4	5	6	7	8	9	9.3
Laws,	d = 0.35	0.70	0.90	1.3	1.7	2.25	3.0	4.3	5.7
Calculated,	d = 0.70	0.86	1.00	1.27	1.66	2.24	3.02	4.38	5.70

Drops larger than 5.5 mm in diameter sometimes occur but they are unstable and will break into smaller drops.

Rain spread--Moisture condensed at lower levels in the ascent of air through the convection tube is carried upward to the hail and snow stages and then, in accordance with the theory of rain formation by BERGERON [1944], the cloud particles are combined into drops as a result of the excess of vapor pressure of supercooled water over that of ice. Drops reaching diameters such that their suspension velocities exceed the ascent velocity are precipitated directly from the convection tube. Smaller drops are carried upward and outward into the outflow layer.

With notation as shown on Figure 7, a raindrop having a terminal velocity v_s in still air, if carried to the top of the outflow layer, will be transported horizontally a distance such that the time of horizontal travel equals the time $\Delta' t$ required for the drop to fall through the outflow layer. When the drop has reached the base of the outflow layer it will be no longer supported by an ascending air current and will fall to the ground at its terminal velocity. No rain will occur from

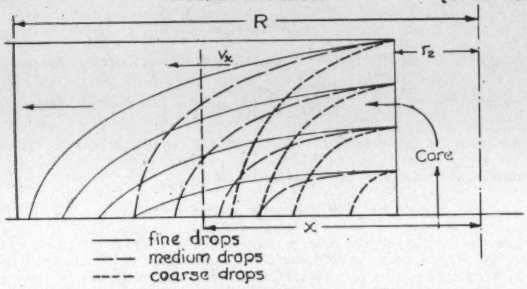

Fig. 7--Trajectories of rain drops in the outflow layer

drops of such size as to evaporate in falling from the base of the outflow layer to the ground. This minimum size of drop will be designated d_0 and may be taken as 1/2 mm diameter, since the drop-size distribution data of BENTLEY [1904], LENARD [1940], and others show that drops of less than this diameter do not usually contribute as much as one per cent of the volume of rain. For this diameter the suspension velocity is 2.3 m per sec. A drop of this size carried upward to the top of the outflow layer will be transported horizontally or radially outward in the outflow layer to a distance or radius R. The radius R fixes the boundary of the area from which rain is precipitated at a given instant. This area will be called the rain spread.

Let x represent the distance from the center of the convective core to any point in the area of the rain spread. Then, from Figure 7, for equal volumes of outflow from the core and for a cylinder of radius x and altitude Δ_2 the following relations may be obtained

$$2\pi \times \Delta_2 v_x = \pi r_2^2 v_a$$

or

$$v_x = r_2^2 v_a / 2\Delta_2 x \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (36)$$

Also

$$2\pi r_2 \Delta_2 v_0 = \pi r_2^2 v_a$$

or

$$v_a = 2\Delta_2 v_0 / r_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (37)$$

and

$$v_0 = v_a r_2 / 2\Delta_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (38)$$

Substituting v_a from (37) in (36)

$$v_x = r_2 v_0 / x$$

If the terminal velocity of drop of diameter d_0 is v_d, the time of fall through the outflow layer will be approximately $t' = \Delta / v_d$. The mean velocity v_a from r_2 to R is

$$v_a = [1/(R - r_2)] \int_{r_2}^{R} v_x dx = [v_0 r_2 / (R - r_2)] \log_e (R/r_2) \quad \ldots\ldots\ldots\ldots (39)$$

But $t' = R - r_2 / v_a$ and $t' = \Delta_2 / v_d$.

Equating these values of t' gives

$$R - r_2 = (v_a/v_d)\Delta_2 = [(\Delta_2/v_d)v_0 r_2/(R - r_2)] \log_e (R/r_2)$$

and

$$(R - r_2)^2 v_d/\Delta_2 v_0 r_2 = \log_e (R/r_2)$$

Since

$$v_0 = v_a r_2/2\Delta_2$$

$$(R - r_2)^2 2v_d/r_2^2 v_a = \log_e (R/r_2) \quad \ldots\ldots\ldots\ldots\ldots\ldots (40)$$

Let $\rho = R/r_2$ and $\rho r_2 = R$. Then

$$(\rho - 1)^2/\log_e \rho = v_a/2v_d \quad \ldots\ldots\ldots\ldots\ldots\ldots (41)$$

Equation (41) permits the rain splash area R to be determined from the ascent velocity v_a. This equation is not readily solved directly from ρ but values of ρ in terms of v_a are given by the line A (see Fig. 8). Line B gives values of $1/\rho^2$, which is proportional to the ratio of rain intensity in the rain spread area to condensation rate in the core. Combining these results the ratio of rain intensity to condensation rate can be expressed in terms of ascent velocity, as shown on Figure 9. The results last given relate to either a stationary storm or to instantaneous values in a moving storm.

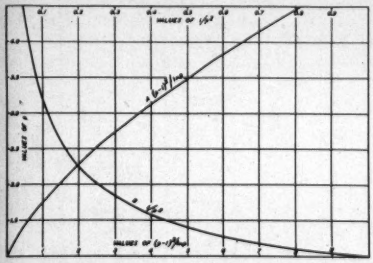

Fig. 8--Values of $(\rho - 1)^2 \log_e \rho$ and $1/\rho_2$

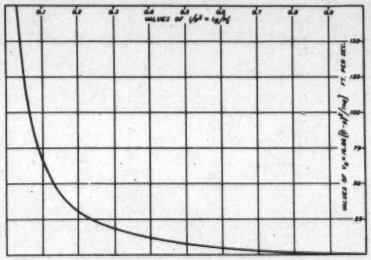

Fig. 9--Values of v_a and $1/\rho^2$

Rain intensity pattern--A rain gage located in the path of the rain splash records a cross section of the storm as it passes. The ascent of air through the convection tube divides the precipitation into two components: (1) Drops with suspension velocities exceeding the ascent velocity. This component is precipitated on the projected area under the convection tube and will be called core rain. (2) Smaller drops, which are carried aloft and precipitated in the outflow layer. This is obviously from the peripheral rain belt surrounding the convection tube, and will be called peripheral rain. It is assumed that sensibly all the rain falls on a rain-splash area equal to the rain-spread area.

Segregation of rain intensity into core and peripheral components provides three main types of a rain-intensity pattern. Typical examples from heavy thunderstorms at St. Louis are shown on Figures 10 to 12. These intensity graphs show numerous rain gushes, usually of one to three minutes' duration, typical of intense thunderstorms everywhere. These rain gushes apparently result either from (1) violent wind gusts in the ascending air current or (2) swaying of the convection tube. On Figures 10 to 12 these rain surges have been eliminated by averaging the rain intensities for five-minute intervals, giving the smoothed graphs shown by dashed lines.

These smoothed graphs reveal the three main types of rain-intensity distribution in thunderstorms: (1) Graphs with a single maximum; (2) double maxima, of which the first is higher; and (3) triple maxima, of which the first is the highest. The occurrence of these maxima is related

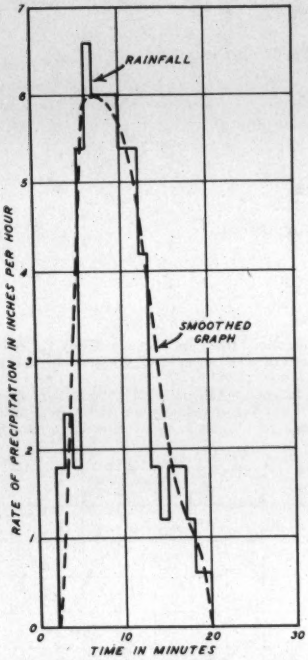

Fig. 10--Rain intensity pattern, Ewing and Washington Block, August 24, 1924

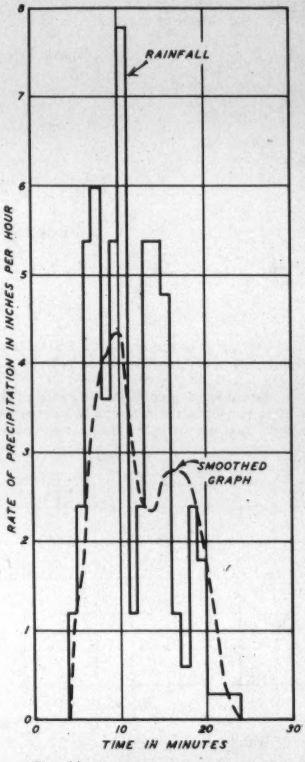

Fig. 11--Rain intensity pattern, City Block 4841, August 24, 1924

to the concentration of rain in the marginal zone between the top of the convection tube and the peripheral belt.

Two factors tend to concentrate high rain intensity in this marginal zone. The first is the concentration of larger drops in the outflow layer close to the convection tube as a result of the greater terminal velocities and consequently smaller radii or horizontal transport of these large drops. The second is the variation of velocity distribution over the cross-section area of the convection tube. For flow in a pipe the maximum velocity is at the center and is approximately 1.19 times the mean velocity, and the peripheral velocity is less than the mean velocity. More of the condensation formed in the tube near the boundary wall is precipitated than in the center of the tube, with a consequent tendency, so far as core precipitation is concerned, to concentrate higher intensities around the circumference of the tube.

Thunderstorms in which there are two rain-intensity maxima, separated by a short interval with either moderate rain or no rain, are extremely common. In the central low-intensity portion of such a rain-intensity pattern (see Fig. 13) rain falls only at such an intensity as is permitted by the ascent velocity of air in the storm core. In more intense storms this may be zero and two wholly separate rain periods result.

Rain-intensity patterns with two maxima occurred in at least 12 out of 25 heavy thunderstorms at St. Louis. Several others were on or near the border line between types 1 and 2. Only two or three were distinctly of the third type, with three maxima.

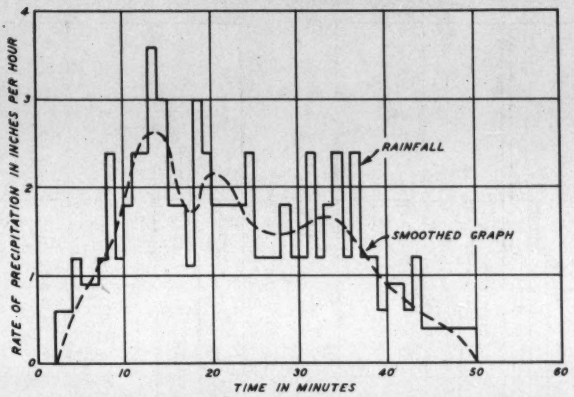

Fig. 12--Rain-intensity pattern, City Block 4841, August 12, 1916

In general the radius of the rain splash in front of the storm is less than behind the storm, the precipitation is more concentrated, rain intensity begins abruptly and reaches a maximum as the edge of the storm core reaches the station. Consequently maximum rain intensity generally occurs early in the course of the passage of a thunderstorm, commonly at about one-third the rain duration, as shown on Figure 13. For storms with two or three maxima the first is usually the highest.

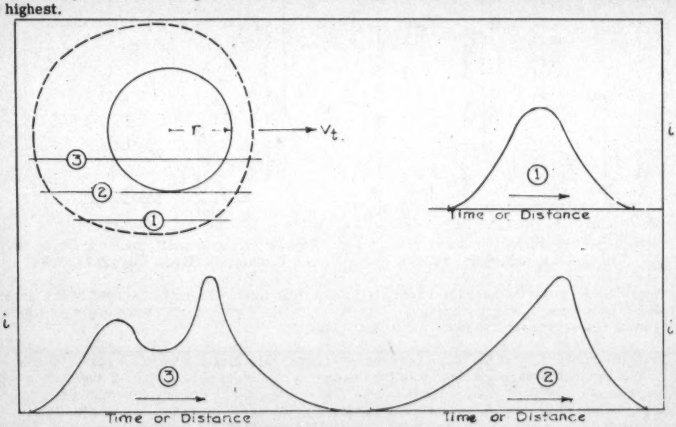

Fig. 13--Rain-intensity patterns

Figures 14 and 15 show rain-intensity patterns for the same storm for two rain gages at different locations in St. Louis. The rain gage at City Block 4841 was apparently located under the path of the core of the storm and is typical of rainfall patterns for this location. The rain gage at Ewing and Washington Block was apparently located outside but near the edge of the core of the storm and is again typical of a rain-intensity pattern for this location. The total rainfall duration was sensibly the same in both cases and both intensity patterns show the rapid variations of rain intensity resulting from gustiness.

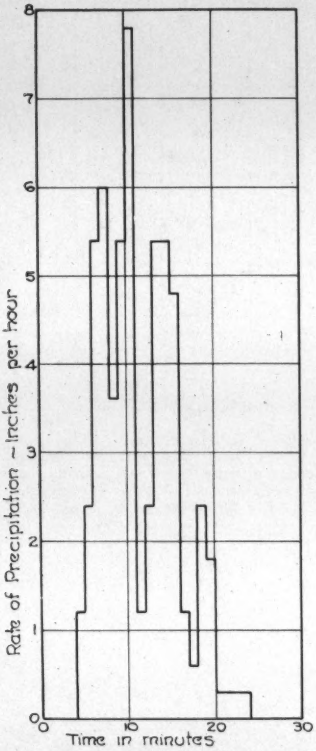

Fig. 14--Rain-intensity pattern, City Block 4841, August 24, 1924

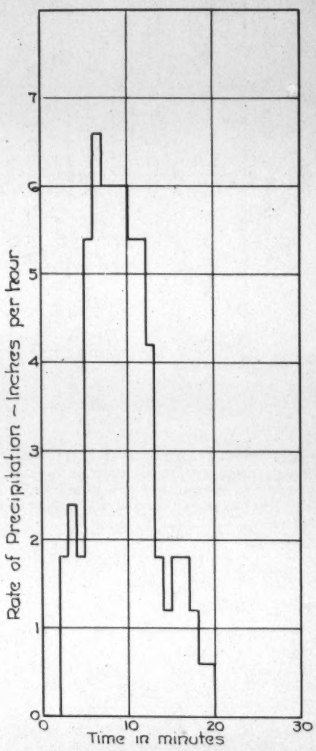

Fig. 15--Rain-intensity pattern, Ewing and Washington Block, August 24, 1924

Figure 16-A shows the average intensity pattern of 26 thunderstorms observed at the Horton Hydrologic Laboratory, near Vorheesville, New York, while Figure 16-B shows average rain intensity in 23 non-thunderstorm rains at the same station.

Intensities occurring at the same percentage of total rain duration were averaged in both cases. The graph for thunderstorms was for heavier storms nearly central over the station and this graph shows a marked central depression. The average curve closely resembles the type curves for thunderstorms with abrupt onset of rain, rapid rise to maximum rain intensity at about one-third the rain duration, and a second smaller maximum intensity following the central depression, the rain intensity then trailing off slowly to zero. The fact that the average of the many storms plotted on the percentage basis has the same characteristics as a typical individual storm shows that these different storms were much alike in rain structure, as if they were models of the same pattern but to different scales.

A rain intensity graph with a single maximum may occur in two ways: (1) With low ascent velocity. Nearly all the condensation is precipitated from the core, giving a single maximum at or near the center of the storm; (2) with a high ascent velocity. Most of the condensation within

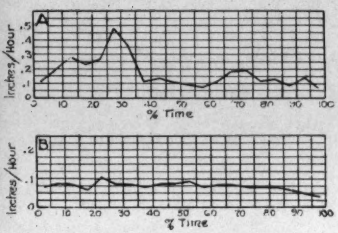

Fig. 16--Comparison of rainfall intensities; (A) thunderstorm intensity; (B) non-thunderstorm intensity

the core is carried into the outflow layer and precipitated from the peripheral belt. With respect to an observer located under the peripheral belt outside the core, as at A1, (see Fig. 13), this will produce a single-crested intensity pattern.

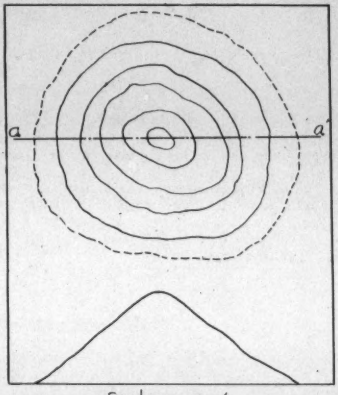

Fig. 17--Storm rain-intensity pattern

A double-crested intensity pattern is produced by a high ascent velocity with respect to an observer located in the path of the core as at 3 on Figure 13. These two patterns obviously merge. With respect to an observer just within the core, there would be only a slight depression of the intensity near the center.

The third, less usual, case of a rain-intensity graph with three maxima appears to be in most cases an intermediate or transitional case between type 1, single maximum, produced by low ascent velocity, and type 2, double maxima, produced by extremely high ascent velocity.

As shown by Figure 8, there is a maximum number of raindrops produced for a single drop size and ascent velocity. If the ascent velocity at the center of the core is near but less than that corresponding to this maximum drop frequency, the precipitation rate at the center of the core may greatly exceed that at the margin of the convection tube, with the result that there will be three rain-intensity maxima.

Wind gusts at the ground surface are usually of short duration, rarely lasting over one minute. Such gusts are apparently responsible, in conjunction with the sorting of raindrops by differences of suspension velocities, both in the core and outflow layer, for most short rain surges lasting from one to three minutes. There may also be longer vibrational swings of wind velocity capable of producing a maximum of rain intensity but usually much less marked than the typical maximum of rain-intensity patterns described.

Prolonged upward swing of the ascent velocity as the core of the storm reaches an observer, followed by a lull while it is passing, can produce a three-crested intensity pattern. The same result would follow if one thunderstorm overtook another, so that the two peripheral belts merge just as they passed the observer. As shown later, a three-crested intensity pattern is possible as a result of a high degree of inclination of the convection core, such that the highest core rain intensity is precipitated outside of and behind the precipitation from both the forward and back portions of the peripheral belt. The relative infrequency of well defined three-crested intensity graphs indicates that the operation of the last three causes named is infrequent.

The convection tube model,(see Fig. 4), accounts for the characteristics, relative frequency and orderliness of thunderstorm rain-intensity patterns. This orderliness can scarcely be fortuitous.

Derivation of storm characteristics from rain-intensity pattern--In addition to the methods given, much may be learned about the dimensions and velocities involved in a thunderstorm by using the rain-intensity graph as a basis. The total rainfall duration t_p at a given location within the rain spread is approximately the time of transit of the rain splash over the station. Rain duration with respect to an observer on the axial line aa' (see Fig. 17), is

$$t_p = 2R/v_t$$

while with respect to an observer at a distance z from the axial line the rain duration is

$$t_p = (2R/v_t)\sqrt{R^2 - z^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (42)$$

For a rain gage in the path of the center of the convection tube the time t_c from the primary to the secondary rain intensity maximum is approximately the time required for the storm to travel a distance $2r_2$ equal to the top diameter of the storm core.

Using notation as shown on Figure 18, the horizontal scale represents time or distance reading to the left from a zero point at the storm front at 0. The vertical scale represents rain intensity.

From the equations

$$\left.\begin{aligned} 2r_2 &= v_t t_c \\ w_f &= \text{frontal width of peripheral belt} = t_f v_t \\ w_b &= \text{rear width of peripheral belt} \quad = t_b v_t \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (43)$$

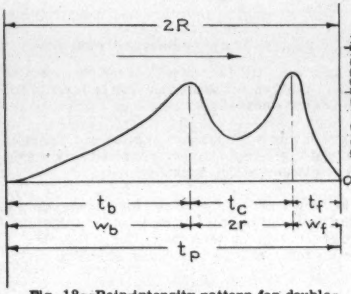

Fig. 18--Rain-intensity pattern for double-crested storm

In addition, the lateral or side width of the peripheral rain splash can be determined from the equation

$$w_\ell = (t_f + t_b)v_t/2 \quad \ldots\ldots\ldots (44)$$

The total width of the storm path is

$$W = 2r_2 + 2w_\ell \quad \ldots\ldots\ldots (45)$$

At a given instant rain is falling on the rain-splash area, which is taken equal to the rain-spread area, or

$$A_s = \pi R^2 \quad \ldots\ldots\ldots (46)$$

As the storm travels, a point on the path of its center records a cross section of the areal rain-intensity pattern. The volume of rain per unit of time on the rain-splash area is C_r.

If the rain-intensity pattern is symmetrical, then this is also equal to the volume of a solid of revolution (see Fig. 17) formed by rotating one-half of the rain-intensity pattern about a vertical axis at the center of the pattern. From the theorem of Pappus or Guldinus, the equation of the volume of a solid of revolution is

$$V_R = 2\pi R_c a_p/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (47)$$

where a_p is the area of the rain-intensity pattern. Then

$$a_p = i_a t_p \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (48)$$

R_c is the distance from the axis of symmetry to the center of figure of a half section. For similar figures this is a constant fraction k_R of the radius R of the rain-splash area. Combining these results gives

$$C_r = 2\pi k_R R i_a t_p/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (49)$$

This equation gives the mass condensation rate C_r in terms of the quantities k_R, R, i_a, and t_p, all of which can be determined from the rain-intensity pattern.

The form of surface of the solid of revolution shown in Figure 17 corresponds to a single-crested rain-intensity pattern or to peripheral rainfall. The same procedure for determining C_r can be applied approximately for a two-crested intensity graph corresponding to the usual rainfall pattern for maximum storms, as shown on Figure 19, with unequal maxima if the vertical axis of the rainfall pattern is so located that the segments on the right- and left-hand sides of the axis are equal and the value of R_c used is the average of the values determined for the right- and left-hand segments.

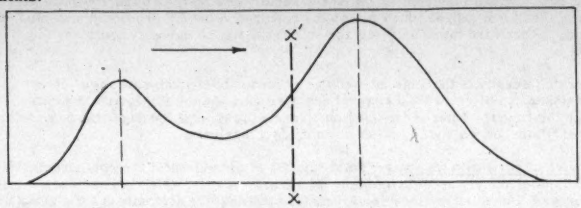

Fig. 19--Storm with two crests

Rains producing maximum splash intensity--For steady conditions in a fully developed storm, C_r is sensibly equal to the total precipitation rate. For a vertically convective storm this rain is spread over an area having a diameter

$$R = r_2 + B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (50)$$

where B is the average width of the peripheral rain belt surrounding the core at outflow level, or

$$B = R - r_2$$

The area of the rain splash is

$$A_s = \pi (r_2 + B)^2$$

Also, as already shown in (13)

$$C_r = \pi r_1^2 v_1 m_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (51)$$

where m_c = moisture condensed out of unit volume of initial air, expressed as equivalent volume of water. If, for example, r_1 and v_1 are in m and m/sec, and m_c in cc, then C_r will be expressed in cc/sec on the area πr_1^2.

In terms of r_2 and v_2

$$C_r = \pi r_2^2 v_2 m_c/\rho_e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (52)$$

The areal average intensity over the rain splash area is

$$I_a = k_c C_r/A_s = r_2^2 v_2 m_c/(r_2 + B)^2 \rho_e \quad \ldots\ldots\ldots\ldots\ldots\ldots (53)$$

where k_c is a proportionality factor to convert mass condensation in the given units of volume into depth in chosen units on the cross-section area of the convection tube.

From (50)

$$B = R - r_2$$

which is a function of v_m/v_d or of v_2/v_d, which r_2 is a function of r_1 and ρ_e. For a given B there will be some value of r_2 for which I_a (see Eq. 53) will have a maximum value. If other factors are assumed constant and r_2 varies, then differentiating and equating to zero to obtain the value of r_2 for which I_g is a maximum gives

$$r_2 = B \text{ or } R = 2r_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (54)$$

or the splash intensity will be a maximum for a storm where the outflow radius of the convection tube equals the width B of the peripheral belt of outflow.

The initial radius of the convection tube, and consequently its outflow radius, is dependent chiefly on irregularities of the stable cover layer. Once formed, it may and probably does enlarge as the storm advances. If the radius r_2 is initially less than B, the value required for maximum point intensity, with the convection tube gradually enlarging, will be a certain point along the course of the storm path at which r_2 has the required value for producing maximum-splash rain intensity. There and there only will the maximum-splash intensity occur for the given conditions.

Point-rain intensity is the time intensity as recorded by a given rain gage. If this gage is on the storm path, it will record a diametral cross section of the rain-splash intensity. The point intensity for the time t_p required for the rain splash to pass over the gage will be a maximum for the same conditions for which the splash intensity is a maximum.

Limitation of core-rain intensity--Total rainfall is comprised of two components: (a) Core rain, which is immediately precipitated, and (b) peripheral rain, which is precipitated from suspension storage. The relative amounts of these components are determined for a given drop-size distribution by the average ascent velocity during the passage of the convection tube over the recording station. Conversely, the average ascent velocity can be determined from the relative proportions of the two rain components.

The condensation rate is an increasing function of the ascent velocity, whereas the fraction precipitated is a decreasing function of the ascent velocity, and their product, which represents the precipitation rate, has a maximum value for some particular ascent velocity v_m.

As a basis of calculation, air saturated at 79.7°F at entry to the convection tube has been used. This corresponds to $e = 1.023$ inch mercury or 25 cm^3/m^3. If 80 per cent of this is precipitable, then $m_c = 20\ cm^3/m^3 = 0.02\ mm/m^2$ depth of condensation per sec for an ascent velocity of one m/sec = 2.84 inch depth/hr on the projected convection-tube area per m per sec ascent velocity.

Using this condensation rate in conjunction with Lenard's drop-size distribution of LENARD [1940] for a severe thunderstorm, calculations were carried out as given in Table 3. Column (3) is the observed number of drops per square meter for each class size; column (4) the volume of drops of a given class size, and column (5) the percentage of total volume of rain included in drops of a given size. The drop size corresponding to the upper limit of a given class is shown in column (6) and the percentage of total volume of rain occurring in drops exceeding a given size in column (7). These results, together with corresponding results from Lenard's series of drop-distribution data are shown on Figure 20. The corresponding suspension velocities, from Laws' data, are given in column (8), and the corresponding condensation rates in column (9). The condensation

Table 3--Rain formation rates with various ascent velocities [LENARD, 1940, p. 155]

Drop diameter	Volume per drop	Number of drops per m^2/sec	Volume	Volume per cent of total	Class limit	Volume per cent larger than limit	Ascent velocity v_a	Condensation rate	Precipitation rate	
1	2	3	4	5	6	7	8	9	10	11
mm	mm^3		mm^3		mm		mps	mm/sec	mm/sec	in/hr
0.0	.....	...	....	....	0.25	100.00	1.25	0.0125	0.0125	1.77
0.5	0.066	514	33.92	0.37	0.75	99.63	3.25	0.0325	0.0323	4.57
1.0	0.523	423	221.23	2.32	1.75	97.31	4.87	0.0487	0.0473	6.68
1.5	1.77	359	635.43	6.66	1.75	90.65	6.08	0.0608	0.0552	7.80
2.0	4.19	138	578.22	6.05	2.25	84.60	7.03	0.0703	0.0594	8.40
2.5	8.19	156	1277.64	13.40	2.75	71.20	7.73	0.0773	0.0550	7.77
3.0	14.2	138	1959.60	20.60	3.25	50.60	8.27	0.0827	0.0418	5.91
3.5	22.5	0	.....	.....	3.75	0	...	.....	.....	...
4.0	33.5	0	.....	.....	4.25	.....	...	.....	.....	...
4.5	47.8	101	4827.8	50.60	4.75	.....	...	.....	.....	...
			9533.84	100.00						

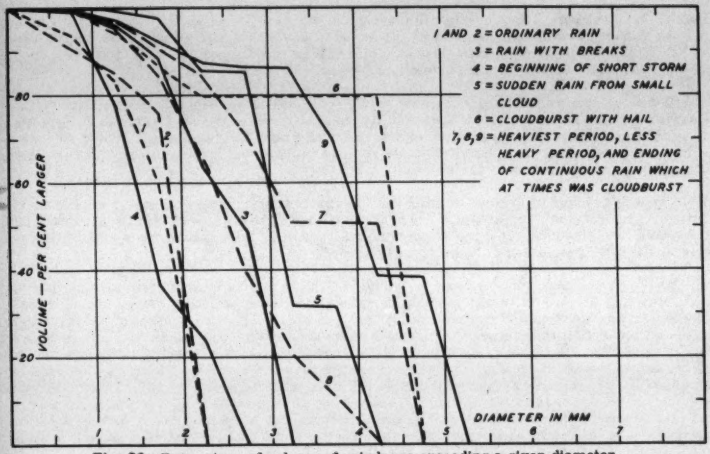
1 AND 2 = ORDINARY RAIN
3 = RAIN WITH BREAKS
4 = BEGINNING OF SHORT STORM
5 = SUDDEN RAIN FROM SMALL CLOUD
6 = CLOUDBURST WITH HAIL
7, 8, 9 = HEAVIEST PERIOD, LESS HEAVY PERIOD, AND ENDING OF CONTINUOUS RAIN WHICH AT TIMES WAS CLOUDBURST
VOLUME — PER CENT LARGER
DIAMETER IN MM

Fig. 20--Percentage of volume of raindrops exceeding a given diameter

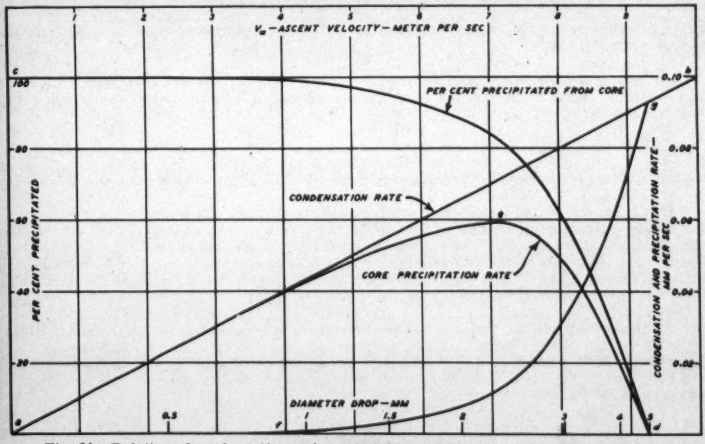
V_m — ASCENT VELOCITY — METER PER SEC
PER CENT PRECIPITATED FROM CORE
CONDENSATION RATE
CORE PRECIPITATION RATE
PER CENT PRECIPITATED
CONDENSATION AND PRECIPITATION RATE — MM PER SEC
DIAMETER DROP — MM

Fig. 21--Relation of condensation and precipitation rates to drop-size distribution; heavy rain period; Lenard storm

rate multiplied by the percentage of total volume having suspension velocities higher than the given ascent velocity and which are consequently able to fall through the ascending air current, represents the rate of precipitation on the projected core area. This is given in column (10). Corresponding core-rain intensities, in inches per hour, are given in column (11). These results are shown on Figure 21. The line ab is the condensation rate, cd the fraction precipitated with the given ascent velocity v_m, and the line aed the precipitation rate on the core area in mm/sec. The

maximum coincident or core precipitation occurs in this case for an ascent velocity of 7.2 m/sec and the maximum core precipitation rate, as shown at the point e, is 0.06 mm depth/sec or 8.5 in/hr. This represents the maximum possible coincident or core precipitation in an ascending air current containing 20 mm of precipitable moisture per cubic m.

It will be seen from Figure 21 that for velocities of ascent v_m less than four m/sec, substantially the entire volume of rain is contained in drop sizes larger than can be held in suspension and is coincidentally precipitated, in other words, as shown by the lines ab and aed, the condensation rate and the coincident precipitation rate for v_m less than four m/sec are identical, unless larger drops are broken up and then carried aloft.

The data used for drop sizes in this study are those storms giving the largest number of large drops. Since only larger drops are precipitated from the core, with high ascent velocities, the precipitation intensity from the storm core will in general be less than that shown by this calculation if the percentage of large drops is less.

Maximum limiting peripheral-rain intensity--A similar limit exists in relation to peripheral-rain intensity. The volumetric intensity of peripheral precipitation equals the fraction of mass condensation not precipitated from the storm core. In Figure 21 the peripheral mass-precipitation intensity is the difference between the ordinate of the condensation line ab and the core precipitation line aed. This is shown by the line fg. This quantity is zero for ascent velocity less than four m/sec and increases to equality with the condensation rate at a velocity of 9.3 m/sec. As the ascent velocity increases, the fraction of peripheral precipitation increases, until, for intense storms with ascent velocities exceeding 9.3 m/sec, there is no core precipitation, a condition not infrequently observed in intense storms. The sum of the core and peripheral components of precipitation for steady conditions equals the condensation rate. As a result of gustiness the actual mass precipitation rate fluctuates above and below the coincident condensation rate.

The important results of this study are as follows:

(1) For steady conditions mass condensation and mass precipitation, expressed, for example, in cm^3/sec are equal.

(2) In case of vertical convection the precipitation intensity on the area over which condensation occurs is, except for low ascent velocities, always less than the volumetric condensation rate over the same area.

(3) Instead of occurring on the area πr_2^2, the precipitation is spread over the larger area $A_s = \pi (r_2 + B)^2$, and for maximum rain-splash intensity, $B = r_2$, the splash intensity is one-fourth the condensation rate if both are expressed in terms of depth on the area within which they occur.

Finally, as a result of a combination of (1) the separation of condensation into ascending and descending components in the storm core and (2) rain spread in the peripheral ring, vertical convection cannot produce an areal-rain intensity on the rain-splash area greater than about one-fourth the condensation rate if both are expressed in units of depth on the area on which they occur. This explains the observed fact that in convective storms, rain intensities usually fall far short of calculated condensation rates.

There are several other reasons why the rain intensity I_a is usually less than one-fourth the condensation intensity c_r: (1) R is usually greater than $2r_2$ when the maximum ascent velocity v_m occurs. (2) There may be dilution of the ascending current of moist air as the result of outside air drawn into the convection tube by turbulence, under certain conditions. (3) The convection tube may not be vertical.

Inclination of convection tube--In the analysis thus far it has been assumed that the convection tube is vertical. This will not be true if, as is frequently the case, the wind velocity w_0 in the outflow layer is different from the translational velocity v_t of the stable cover layer.

Figure 22-A and 22-B shows, respectively, elevation and plan of thunderstorm model with an inclined convection tube, it being assumed for simplicity that the convection tube has a uniform diameter $2r_m$ equal to twice the mean radius. Letters with primes will be used to designate quantities related to the inclination of the convection tube, for which the same symbols without primes apply to a vertical convection tube. For a given thickness Δ of the moist air layer and height h_t of the tropopause, the lift L will be unchanged but the length of the convection tube will be increased to L'.

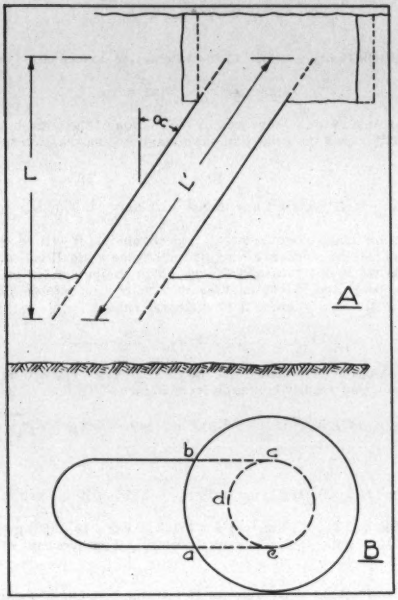

Fig. 22--Inclination of convection tube

$$L' = L \sec \alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (55)$$

For the same pressure difference at the ends of the convection tube the hydraulic gradient is decreased by inclination of the tube from $(P_1 - P_2)/L$ to $(P_1 - P_2)/L'$, or in the ratio

$$L/L' = \cos \alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (56)$$

(The author seems to be in error here in treating the convection tube like a pipe with a hydraulic gradient, so (56) and those that immediately follow do not apply. The driving force in a convective tube without sides is not the hydraulic gradient but the density (mostly thermal) difference between the air in the column and that outside. A leaning tube is the combined result of unchanged convective ascent and horizontal shear of the country wind. None of the force of the convection is used or lost except through such turbulence as the shear introduced in the wind. The author's computations of the reduction of areal or splash rain and the increase in core-rain intensity are accordingly too great.--C. F. Brooks)

Since the mean velocity is proportional to the square root of the hydraulic gradient, the mean velocity will be reduced from v_m to v'_m, where

$$v'_m/v_m = \sqrt{L/L'} = \sqrt{\cos \alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (57)$$

The volumetric condensation rate C_T is the product of $(m_C) \times$ (cross section of convection tube, measured horizontally) $\times$ (vertical component v'_v of mean velocity). The vertical component of the mean velocity is

$$\left.\begin{aligned} v'_v &= v'_m \cos \alpha \\ &= v_m \cos^{3/2} c \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (58)$$

where v_m is the ascent velocity for a vertical tube. The horizontal cross section of the convection tube is elliptical. Its axes are $2r_m$ and $2r_m \sec \alpha$ and its area is

$$A_c = \pi r_m^2 \sec \alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (59)$$

The product of (58) and (59) is proportional to the volumetric condensation rate. This gives

$$C'_r = m_c \; r_m^2 v_m \sqrt{\cos \alpha}. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (60)$$

The volumetric condensation rate is decreased by inclination of the convection tube in the ratio $\sqrt{\cos \alpha}/1$. For different angles the reduvtion of volumetric condensation rate is as follows:

α =	0°	10°	20°	30°
C'_r/C_r =	1.0	0.992	0.969	0.930

Inclination of the covection tube exceeding 30° is improbable and it will be seen that so far as volumetric condensation rate is concerned, inclination causes a small but only a small reduction. This condensation is spread over a rain-splash area which comprises the projected peripheral ring plus the part of the projected convection tube area which lies outside the ring. The projected convection tube area will lie wholly inside the peripheral ring if

$$L \tan \alpha < r_m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (61)$$

If $L \tan \alpha \geq 2r_m$, an area of the projected convection tube $\geq \pi/2 - r_m^2$ will be outside the peripheral ring. For this condition it can readily be shown from Figure 22-B that

$$A'_s/A_s = (4.5\,\pi - 4)/4\pi + L \tan \alpha/2\pi r_m \quad \ldots\ldots\ldots\ldots\ldots \quad (62)$$

or

$$A'_s/A_s = 0.81 + L \tan \alpha/2\pi r_m = 0.81 + 0.159\, L \tan \alpha/r_m \quad \ldots\ldots\ldots \quad (63)$$

For example, for L = 9.42 km, r_m = 1 km, tan α = 0.212 and α = 12°, (63) gives A'_s/A_s = 1.13 and there would be a decrease of rain-splash intensity resulting from increase of projected rain-splash area alone of 13 per cent.

Finally, for small inclinations of the convection tube the reduction in splash-rain intensity by inclination is so small as to be practically negligible, while for maximum inclinations of the convection tube ranging up to 20 to 30° the effect of increased splash area may reduce the areal or splash-rain intensity by 25 per cent or more. This result is in accordance with experience, since maximum rain intensities in the Rocky Mountain region, where there is little wind shear aloft and convection is nearly vertical, are commonly greater than for the eastern United States, with nearly the same vapor pressure but with marked inclination of the convection tube in some storms. That the inclination of the convection tube is usually small or moderate is indicated by the following considerations.

Assuming that at any given level a particle of moist air ascending with a velocity v_m takes on a horizontal component of velocity equal to that of the country air at the same level, then the convection tube will gradually increase in inclination proceeding upward, until at the outflow level, where $w_h = w_0$, the inclination will be such that

$$\tan \alpha = w_0/v_m$$

Since v_m is usually large, and in some cases extremely large, relative to w_0, the inclination angle α in most intense storms will be negligibly small.

The things compared above are the average areal intensities over the rain-splash area, while rain intensities as ordinarily compared are maximum point intensities as recorded at a given rain gage. For circular rain splash areas these two quantities, as already shown, bear nearly a constant relation to each other. If the rain-splash area is not circular but has a distorted form, as shown by Figure 22-B, as a result of inclination, the characteristics of rain distribution in the rain-splash area will be modified in the following various ways.

(1) The outflow ring may be shifted to the right, as shown by dotted lines on Figure 22-A. This will result from the increased component of horizontal outflow velocity v_0 to the right and a corresponding decrease to the left as a result of inclination of the convection tube. This will tend to

increase the ratio A'_S/A_S and to decrease the average rain-splash intensity for an inclined tube more than is indicated by (63). The increase of volume and velocity of outflow at the front and the decrease of these quantities at the back of the rain splash by inclination may be compensated by a corresponding increase of thickness of the outflow layer at the front as compared with that at the back. So far as this effect considered alone is concerned, inclination of the tube tends to concentrate the highest rain intensities at the front of the storm and to make the primary maximum rain intensity greater than the secondary maximum, as it usually is.

(2) As a result of reduction of ascent velocity by inclination, smaller drops will be precipitated from the convection core and the percentage of condensation appearing as core rainfall will be increased.

(3) Other factors are involved. Shifting of the peripheral belt in the direction of inclination tends to concentrate peripheral rain at the front. At the same time the peripheral and core rain overlap and commingle in the region abcde (see Fig. 22-B) of the rain splash. This may produce (a) a higher maximum-point intensity in the second than in the first maximum, reversing the more usual condition; (b) this produces a marked difference of drop-size distribution in the regions of the two maxima. (It is to be remembered that the rain-intensity splash as ordinarily plotted, with time reading from left to right, is a mirror image of the splash as it actually occurs with the storm traveling from left to right.)

Lightning

The preceding theoretical treatment of the operation of a model thunderstorm shown on Figure 4 provides a basis for application to the quantitative analysis of thunderstorms to the determination of their dimensions, velocities, and precipitation characteristics. Three topics closely related to the physics of thunderstorms have not been treated in detail as they are not closely related to rain production. These are: (1) Statistical distribution of drop sizes and the occurrence of dominant drop sizes; (2) rain-intensity distribution within the rain splash and over the rain smear area; (3) lightning. The first two topics are the subjects or separate papers. Both afford confirmatory evidence of the validity of the tubular thunderstorm model.

With regard to lightning, it will be assumed that the principal source of electricity of lightning is the Lenard effect or the release of electrons by the breaking up of unstable or over-size raindrops. In accordance with the author's thunderstorm model this will produce the following effects: (1) Positively charged broken drops are either slowly carried upward from the convection tube to the outflow layer or are precipitated as core rainfall, depending on the strength and succession of gusts. (2) Electrons released by the breaking of unstable drops in the convection tube will be rapidly carried upward to the outflow layer, where they will tend to remain. (3) Additional electrons will be released as the result of combination and subsequent breaking up of large drops in the peripheral belt, particularly close to the margin of the convection tube. These electrons will be carried horizontally outward in the outflow layer but will tend strongly to accumulate at the front of the outflow layer. (4) Positively charged droplets from these sources will be precipitated from the core and peripheral ring. These conditions provide (a) juxtaposition of positively charged rain descending from the peripheral ring and free electrons ascending within the convection tube; (b) negatively charged rain in the inner portion and positively charged rain or cloud in the outer portion of the peripheral ring, resulting from smaller or broken, and hence positively charged, drops traveling farthest horizontally.

A theory of the formation of lightning, presented by SIMPSON [1910] in 1906, has been subject to much criticism, chiefly on the ground that it did not provide a sufficient variety of conditions of occurrence of lightning in thunderstorms. The author's thunderstorm model provides a combination of conditions under which lightning may occur from cloud to earth, cloud to cloud horizontally, or cloud to cloud vertically, depending largely on the ascent velocity and fraction of the rain which is broken up in the convection tube and outflow layer.

Observations at Kew Observatory, by means of instruments carried on sounding balloons, have been reviewed by ROBINSON [1941]. Diagrams are given by Robinson showing a maximum frequency of positive field at height of about seven km, decreasing to zero above 12 km, also a maximum frequency of positive field close to the storm center and a still higher maximum at the extreme outer radius of the rain splash. These results are in agreement with the conditions resulting from the operation of the author's thunderstorm model.

Snow and, in particular, soft hail, are often positively electrified by friction [SIMPSON, 1942]. Also, because of its lightness, snow is carried horizontally to the outer limit of the peripheral belt.

A combination of this with positive electrification of larger raindrops in and around the storm core produces, as a statistical average, a maximum of positive electrification near the center and a stronger maximum at extreme periphery of the storm, as shown by the Kew observations, reported by ROBINSON [1941].

SIMPSON [1942] has reviewed the evidence regarding the nature of lightning which has accumulated since the original publication of Simpson's theory. He concludes, among other things, that (1) precipitation of all kinds is sometimes positively and sometimes negatively charged, (2) in all kinds of rain the amount of water which is positively charged is greater than the amount which is negatively charged, (3) positive charges on rain preponderate in thunderstorms, especially in the period of high rain intensity. Changes of electric charge are associated with (a) wind gusts, (b) abrupt changes of rain intensity, (c) changes of drop size and drop-size distribution.

The occurrence of strong and prolonged wind gusts must be taken into account in conjunction with the results of the subdivision of rain into core and peripheral components in order to arrive at a set of conditions which is comportable both with the phenomena of lightning and the observed electric fields in thunderstorms and electric charges on rain.

Lightning seems specially likely to occur when an ascending air gust in the convection tube charged with free electrons or negatively charged particles passes a descending peripheral gush of positively charged rain which has resulted from the collision and subsequent breaking up of large raindrops around the inner margin of the peripheral ring. In this way the frequent occurrence of rain gusnes following violent lightning is easily understandable.

While the physics of lightning is too complex to be completely treated here, the idea that rain is subdivided into two components, (1) that precipitated from the convection core, (2) that precipitated from the peripheral belt in the outflow layer, not only leads to results consistent with observations but apparently contributes directly to a satisfactory interpretation of the observed phenomena of lightning.

Gustiness--The author's thunderstorm model assigns much importance to gustiness of thunderstorm winds both as a determinant of the type of the resulting storm and in relation to lightning phenomena. Further study of gustiness and correlation of wind gusts, rain gushes, and lightning flashes on a quantitative basis is much needed. In case of rain gushes the author and others have found that if rain intensities are plotted between each two major breaks of intensity, taking times to the nearest whole minute, a reasonably accurate detailed rain pattern is obtained. Also if the intensities are averaged for five-minute intervals the rain gushes are mostly eliminated. Using, for example, the rain pattern shown on Figure 23,

N = number of rain gushes or summits = 10
i_g = average crest intensity = 2.28 in/hr
i_0 = average trough intensity = 1.15 in/hr
i_a = average rain intensity = 1.44 in/hr
t_p = total rain duration = 48 min = 0.8 hr
Average range = $i_g - i_0 = 1.13$
Relative range = $(i_g - i_0)/i = 0.78$
Gush interval = $t_g = t_p/N = 48/10 = 4.8$ min = 0.08 hr
Gush volume = $(i_g - i_0)\, t_g/2 = 0.045$ in
Relative gush volume = $(i_g - i_0)/2\, t_g/t_p = 0.058$.

If some similar method can be applied to the more complex and irregular wind gusts it would provide a basis of correlation of the two quantities.

The formation of a tubular sheet vortex in thunderstorms and hailstorms is apparently the result of air ascending through the break in the cover layer in successive gusts. (An alternative hypothesis is that these variations in precipitation rate are due to horizontal convergences and divergences in the turbulent wind.-- C. F. Brooks). The origin of these gusts presents an interesting problem.

While not qualitatively proven for air, it is well established both theoretically and experimentally that the flow of water under certain conditions cannot be steady, but initially steady flow breaks up into roll waves or into a train of roll waves [CORNISH, 1910]. JEFFREYS [1925] concluded that for the flow of water, wave trains form when the conditions are such that $v \geq 2\sqrt{gd}$ or when the velocity for steady flow, if it existed, would be twice the velocity $\sqrt{gd}$ of a long wave in still water. This result has been roughly found experimentally by CORNISH [1925]. If a similar criterion exists in case of the formation of wave trains in air, then the conditions favorable to the occurrence

of hailstorms or thunderstorms will be the combination of a relatively shallow surface layer of air and a layer of convective instability reaching exceptionally high.

The occurrence of rain in gushes in thunderstorms is a common phenomenon and the rain gushes apparently reflect the effects of individual air gusts ascending in the convection tube but are often of longer duration, commonly one to three or four minutes, whereas wind gusts accompanying thunderstorms, and neglecting minor gustiness which is superposed on the main or longer gusts, are commonly of shorter duration, usually less than one minute. Sometimes in violent

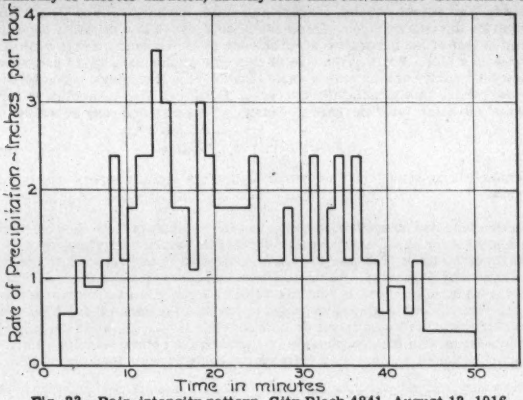

Fig. 23--Rain-intensity pattern, City Block 4841, August 12, 1916

thunderstorms strong wind gusts are repeated at irregular intervals, averaging a few seconds, although other gusts may last for several minutes. That rain gushes should be of longer duration than the wind gusts which produce them results at least in part from the fact that a wind gust entering the convection tube accelerates the upward flow of air throughout the entire length of the convection tube, although the duration of the gust may be much less than the time required for a particle of air to flow from the entrance to the outlet of the convection tube. The effect on the rain pattern is the production of a rain gush often of longer duration than the wind gush.

Thunderstorm life histories

Thunderstorms may occur singly or in groups or chains. Several simultaneous thunderstorms are attributed to widespread favorable conditions, that is, with both parents, namely, the requisite stable cover layer and the requisite underlying moist air layer, present over a wide area, with thunderstorms arising at weak spots in the cover layer, this giving rise to what may be called a "litter" of thunderstorms.

Thunderstorms may and probably do die out as a result of: (1) Exhaustion of the supply of warm moist air, particularly in case of local convective storms, or (2) the termination of suitable conditions aloft. With widespread favorable conditions the question naturally arises: Why do not the individual storms expand and merge into one enormous storm? The author has repeatedly seen two thunderstorms crossing a given line simultaneously and only a few miles apart, yet they rarely if ever merge.

It has been shown that there is a certain storm-core diameter which gives maximum rain intensity. BRANCATO [1942] reports the results of a study of over 100 non-frontal thunderstorms in the Muskingum Drainage Basin, Ohio, using the United States Soil Conservation Service network of rain gages. These storms had an average width of rain splash of about six mi, with a maximum of 12 mi. Storms originating within the Muskingum Basin usually produce appreciable rainfall for not over two hours and attain maximum rain intensity within one hour.

In case of thunderstorms, as in all cases of convection, there is a return flow of air somewhere, replacing the air flowing upward through the convection tube. As far as rain production is concerned, this return current may be considered as a gradual settling down of the air surrounding the convection tube.

The surface of discontinuity between the upflow and downflow or return current may be of at least three kinds, depending on relative velocities and density differences in and outside the core: (1) A wavy surface surrounding the core; (2) vortex rings thrown off near the boundary into the less dense fluid in the convection tube, producing ordinary turbulence; and (3) a tubular sheet vortex may separate the two surfaces. This case is considered in a separate paper. The case here considered is that of the generation of turbulence at the boundary and is analogous to turbulent flow of water in a pipe. For a given size of convection tube and a given pressure difference, $P_1 - P_2$, the ascent velocity attains such a value that Force = Resistance. The Manning formula for flow of liquids, which is dimensionally correct in form, can also be applied to air with appropriate constants to allow for difference of density. This equation may be written

$$v_m = (c/n)(r/2)^{2/3}\sqrt{(P_1 - P_2)/L} \quad \ldots\ldots\ldots\ldots\ldots\ldots (64)$$

where c is a numerical constant (1.486 for water) and n is a factor proportional to the surface resistance to flow.

The convection tube has no solid boundaries and the velocity of flow relative to the walls is the sum of the ascent velocity v_m and the mean descent or return velocity v_r outside of but adjacent to the walls of the tube. The distribution of velocities in and adjacent to the convection tube is somewhat as shown by Figure 24. As the radius r increases, for the same ascent velocity v_m, the velocity v_r must increase, since the outflow velocity for a given v_m increases as the radius r increases. If the return current always extended to the same distance D from the center of the core, then the return velocity would increase in proportion to v_m. If, as is certainly the case, the distance D increases with the ascent velocity v_m, then the return velocity v_r will increase in proportion to some power of v_m less than unity but probably greater than one-half.

v_m is the ascent velocity relative to the Earth. The ascent velocity relative to the boundary of the convection tube is

$$v_b = v_m + v_r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (65)$$

or, in terms of the Manning formula, the value of v_b is

$$v_b = v_m + v_a = (c/n)(r/2)^{2/3}\sqrt{s} = k_1 r^{2/3} \ldots\ldots\ldots\ldots\ldots (66)$$

where k_1 is constant for a given storm.

$$k_1 = (c/n)\sqrt{s}/2^{2/3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (67)$$

Substituting $v_d = k_2 r^m v$ gives

$$v_m = k_1 r^{2/3}/(1 + k_2 r^m) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (68)$$

Differentiating and making $dv_m = 0$ to obtain the value of r for maximum ascent velocity gives

$$r_g = \sqrt[m]{1/(3k_1 k_2 m/2 - k_2)} \ldots\ldots\ldots\ldots\ldots\ldots (69)$$

In (69), r_g is the mean radius of the convection tube for which the mean velocity of ascent relative to the Earth is a maximum. Data for numerical solution of (69) are not available. The analysis, however, is strictly rational in form for the hydrodynamic model and holds true for actual thunderstorms if they reproduce the same conditions. This analysis demonstrates the existence of a convection-tube radius for which the ascent velocity is a maximum. This may or may not be precisely the radius for which the rain intensity is a maximum but will not differ greatly from it.

Without going into detailed analysis it can readily be shown that there is also a maximum rain-splash radius R. The four maxima involved, namely, maximum ascent velocity, maximum rain intensity, maximum mass-condensation rate C_r, and maximum storm radius R, are closely related but not identical although they apparently occur at about the same stage of development of the thunderstorm.

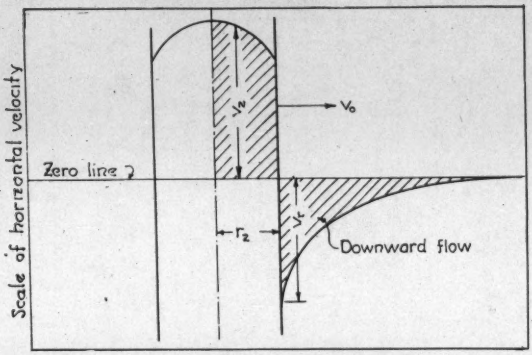

Fig. 24--Velocity distribution adjacent to outflow from convection tube (schematic)

The resistance resulting from falling rain is also a factor in limiting growth and diameter of thunderstorms. For large ascent velocities the rain is mostly peripheral and the most intense rain is concentrated close around the walls of the convection tube as a result of the sorting of raindrops by horizontal flow in the outflow layer. This occurs to an increasing extent as the diameter of the storm core increases, since the rain production for a given ascent velocity increases as the square of diameter of the convection tube, while the circumference of the convection tube varies directly as the radius. Other things equal, the intensity of peripheral rain close around the convection tube increases as the radius r. Descending rain produces a descending air current and operates in the same way as the convective return current in limiting the size of the storm. Since each of the quantities v_m, i_g, C_r, and R has a maximum value, a thunderstorm starting with a small core radius will increase in diameter and intensity until these various maxima are attained. Thereafter the ascent velocity and energy of the storm decrease and with it the outer radius R, until the storm becomes too weak to be longer sustained.

This in part accounts for the fact that storms in a different group or chain do not merge, at least they do not merge if the distance between their centers is greater than the sum of their maximum radii. However, there is another factor involved, which will next be considered.

The entrance to and outflow from the convection tube constitutes a sink and source. If two storms are near each other, then there will be two adjacent sinks at the surface and two adjacent sources at the outflow level. Two sources or two sinks tend to repel each other if their fields overlap. Two equal storms traveling in adjacent parallel paths will tend to remain at a distance from each other at least equal to the sum of their radii of influence. This radius may be determined as follows. The radial lines of flow around the outflow or source will be essentially the same as those of an electric or magnetic field where the source moves relative to the field. A more obvious analogue is afforded by the lines of flow around a well in a moving ground-water field. The lines of flow around a source are similar to those around a sink but with their directions reversed. Figure 25 shows the lines of flow around a source, moving forward with respect to its field, corresponding to outflow in a case where the motion of the cover layer in a storm is greater than that of the sub-stratosphere layer. The heavy dashed line shows the boundary of the outflow stream from the source. At an infinite distance behind the source the two branches of this boundary line become asymptotic to two parallel lines separated by a distance W. The limiting width W of the outflow stream is such that the volume of flow in the outflow layer in the width W equals the volume of outflow from the source. Within the dashed boundary line and in front of the source the flow lines curve backward, as shown. (A method of plotting these lines for a ground-water field with laminar flow has been described by SLICHTER [1905].)

It can readily be shown that the equation of the line forming the boundary of the outflow is, in radian measure

$$x = y \tan \pi (1/2 - 2y/W) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (70)$$

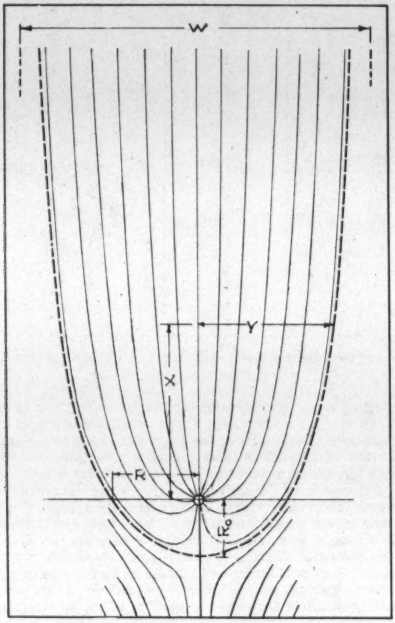

Fig. 25--Lines of outflow from a source in motion relative to its field

The width of the outflow at x = 0 or at the source is

$$2R_1 = W/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (71)$$

and directly in front of the source

$$R_0 = W/2\pi = 0.159\ W \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (72)$$

From the preceding considerations it will be seen that the boundary line of the splash will be either the boundary of the outflow layer or the boundary defined by the precipitation radius R, whichever is smaller. If the boundary of the outflow layer lies inside of R, as is apparently often the case at the front of the storm, precipitation may begin abruptly. At the sides precipitation may end abruptly at a certain distance W/2, so that an observer nearly underneath this boundary may observe rain from suspension storage persisting steadily for some little time on one side of a pond, with none on the other side, or even rain on one side of a highway, with none on the other side.

The hydrodynamic model of a thunderstorm fully accounts for the observed facts regarding the life histories of thunderstorms and the fact that they follow parallel courses without merging, without assuming that the elimination of one of the two controlling conditions, that is, cover conditions and heated moisture layer, although disappearance of either one or both of these conditions affords additional reasons for the dying out of thunderstorms.

Thunderstorms, like most natural phenomean, are definitely ordered, in accordance with physical laws, yet their phenomena and life histories are almost infinitely varied.

APPENDIX I

Notation

Unless otherwise specified, foot-second units are used for flow conditions, and inches per hour for condensation and rainfall rates. Special symbols are defined where used in the text.

Subscripts 1 and 2 refer to conditions at inlet and outlet ends of convection tube.

Subscripts c, f, and b refer to conditions at center, front, and back of storm core or outflow area, as specified.

A	Area of rain smear or total area on which rain falls in a given storm
a	Cross-section area of convection tube
a'	Acceleration of the air caused by the falling rain
α	Angle of inclination of axis of convection tube to the vertical
A_p	Projected area of convection tube
A_s	Area of rain spread
B	Width of peripheral rain-belt in outflow layer
C_a	Condensation rate on projected area of convection tube
C_r	Total condensation rate in convection tube, volume per unit of time
c_m	Condensation rate on mean section of convection tube, in/hr
c_r	Condensation rate on inlet section of convection tube, in/hr
c'_r	Condensation rate in convection tube, expressed as depth on cross-section area at outflow level
Δ_1, Δ_2	Thickness of inflow and outflow layers, respectively
d	Diameter of raindrop, in millimeters or as specified
d_0	Minimum diameter or precipitated droplets
e	Vapor pressure, mb or inches of mercury, as specified
h_c	Height of condensation level
h_t	Height of base of stratosphere
θ_d	Dew-point temperature, °F
θ_K	Absolute temperature, Kelvin
i	Rain intensity for time unit, specified
i_{av}	Average station rainfall for a time interval
i_g	Maximum station intensity for time unit, specified
i_s	Average rain intensity at a given moment over the rain-splash area
J	Barometric jump, mb
L	Lift = vertical length of convection tube, center of inflow layer to center of outflow layer
L'	Actual length of inclined convection tube
m	Moisture content at saturation, gm/m^3
m_c	Condensible moisture, gm/m^3
P	Barometric pressure, mb
p	Total rainfall at a given station
p_0	Total rainfall at the eye or point of maximum rainfall in the rain smear
R	Radius of a circle having a cross-sectional area equal to that of the rain splash
R_g	Gas constant
r_1, r_2	Radius of a cricle having a crosss-sectional area equal to that of base and top of convection tube, respectively
r_m	Mean radius of convection tube
r_0	Radius of a circle having an area equal to that of the rain smear
ρ_1	$= R/r_1$; $\rho_m = R/r_m$
ρ_e	Expansion ratio
T	Time of transit of rain splash over station
T_K	Absolute temperature, Kelvin
T_s	Surface air temperature, Kelvin
t_1, t_2	Times of occurrence of corresponding phenomena at front and back of convection tube as it passes an observer on the axial line, that is, maximum wind velocities, or maximum rain intensities
t_p	Rainfall duration
V	Volume
v_1, v_2	Ascent velocities at entrance to and exit from convection tube, taken as center of inflow and outflow layers
v'_d	Terminal velocity of drops of minimum size

v_f, v_b	Horizontal velocity of flow across wall of convection cylinder at inlet level, front and back
v_g	Maximum ascent velocity in core
v_h	Horizontal velocity across wall of convection tube at height $\Delta/2$
v_m	Mean velocity of upward flow in convection tube
v_0	Average velocity of outflow through the walls of the convection tube in the outflow layer
v_s	Suspension velocity
v_t	Translational velocity of core of storm
v_x	Velocity at radius x in core or outflow
w	Wind velocity, relative to Earth, mi/hr
w_b	Ground wind velocity, back of convection tube
w_c	Horizontal wind velocity at center of core
w_f	Ground wind velocity, front of convection tube
w_0	Wind velocity at outflow level
x	Mixing ratio, also for radius as indicated by context

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IONIZATION DURING THUNDERSTORMS AT THE HUANCAYO MAGNETIC OBSERVATORY

W. D. Parkinson

During the months of May, June, July, and August 1947, continuous recordings of the rate of ion formation in the atmosphere were made at the Huancayo Magnetic Observatory in Peru. The equipment used consisted of an air-tight cylindrical ionization chamber made of coarse mesh wire netting, and covered with thin cellophane. The stopping power of the cellophane for alpha rays is equivalent to 1.5 cm of air. The walls of the chamber were held at a potential of 90 volts, positive with respect to ground. A central insulated rod was connected to a unifilar electrometer. This is grounded at the beginning of each hour, and left insulated six min after the hour. During the remaining 54 min, the central rod collected positive ions at a rate proportional to the rate of ion formation inside the chamber. Electrometer deflection was continuously recorded on a photographic trace. Since the charge remained on the rod and electrometer fiber, the trace effectively integrated the rate of ion formation during the 54-min period.

The equipment was out of doors, but under a tile roof to protect it from rain. It was exposed to wind from every quarter. The lowest part of the chamber was about one m above the ground. The range in air of alpha particles from radioactive substances normally found in the air varies from 3.9 cm (for radon) to 6.6 cm (for radium C). Hence sources of alpha radiation will affect recorded values only if they are within a few cm of the chamber. A source of alpha rays located on the ground will not affect the instrument. However, beta and gamma rays from the ground will contribute to the measured ionization. Further details of the instrument are given elsewhere [TORRESON, 1939, p. 264].

Ionization during thunderstorms--WAIT and McNISH [1934] have found an increase in the atmospheric ionization at Washington during a thunderstorm accompanied by precipitation. Similar effects were observed at Huancayo. Of 12 close thunderstorms, eight were accompanied

Table 1--Meteorological conditions and accompanying effects on atmospheric ionization

Date	Weather	Increase in ionization
1947		pct
May 8	Thunderstorm and rain	40
9	Light rain	Slight increase
25	Rain	Slight increase
26	Close thunderstorm with heavy rain	Great increase[a]
June 3	Clear	60
8	Thunderstorm	0
13	Rain	40
15	Close thunderstorm with rain	20
16	Thunderstorm with light rain	0
17	Light rain	60
July 1	Thunderstorm with heavy rain	Great increase[a]
2	Thunderstorm	0
28	Thunderstorm and rain	0
30	Distant thunderstorm	30
Aug 1	Distant rain	100
14	Distant rain	100
17	Clear	30
23	Clear	100
27	Thunderstorm with rain and hail	Great increase[a]
29	Clear	50
30	Brief thunderstorm	10 (doubtful)
31	Distant thunderstorm	30

[a]Increases of several times normal ionization were recorded. An analysis of these is presented in more detail.

by an increase in ionization, usually of from 50 to 100 per cent of the normal value. Also on 18 occasions when similar increases were recorded, 14 were accompanied by a thunderstorm or rain. Table 1 gives a summary of results.

Graphs of instantaneous values of ionization on these three occasions are shown in Figure 1. As has been pointed out, the recorder itself does not give instantaneous values of ionization but effectively integrates this value. Some inaccuracy is inevitably introduced in transforming the trace to instantaneous values. This however should not be sufficient to affect the general shape of the curves.

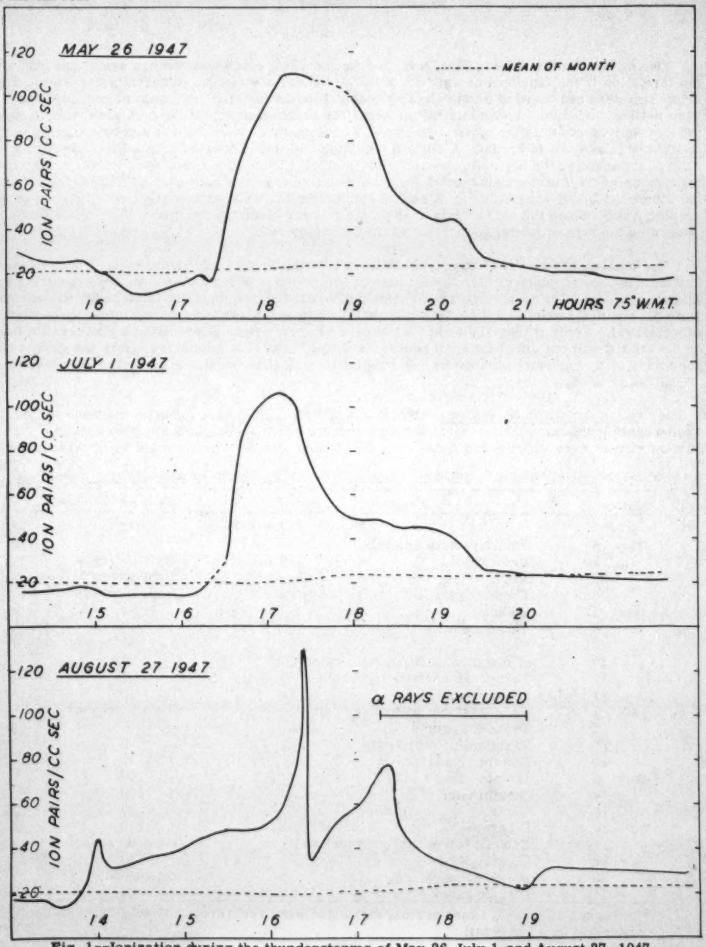

Fig. 1--Ionization during the thunderstorms of May 26, July 1, and August 27, 1947

It will be seen that the peak values of ionization are some five times the normal values, and the decrease to normal values are more or less exponential. Wait and McNish found that the decay curve of additional ionization agrees with that for radium B. The decay periods of these curves for May 26 and July 1 also agree well with the decay period of a mixture of radium B and radium C, such as would be present after the introduction of radium B into the air.

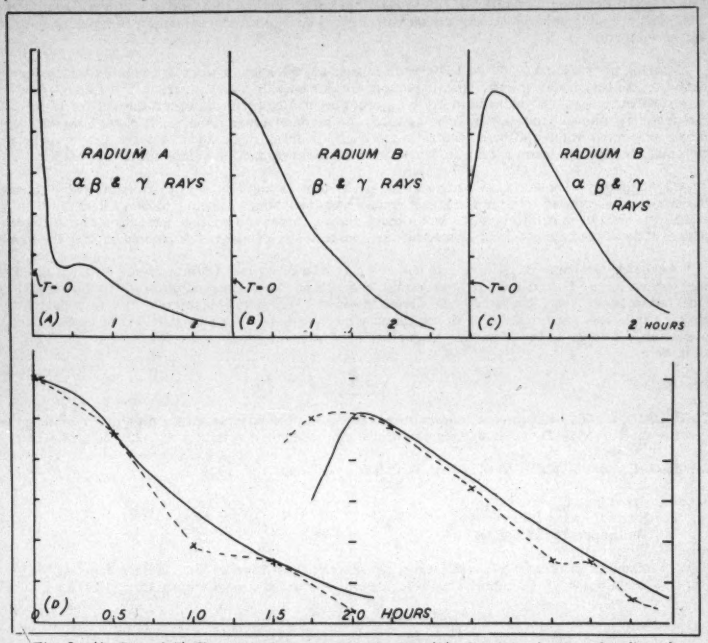

Fig. 2--(A, B, and C) Theoretical curves of ionization (A) after introduction of radium A, if chamber is sensitive to α, β, and γ rays; (B) after introduction of radium B, if chamber is sensitive to β and γ rays; (C) after introduction of radium B, if chamber is sensitive to α, β, and γ rays; (D) fit of data of May 26, 1947 to curves (B) and (C)

Two possibilities present themselves: either the rain contains radium B, which it carries to the ground, whence it ionizes the air, or radium B is somehow introduced into the air. In the former case the ionization chamber will be subject to β and γ rays from the falling rain, and from water on the ground. If the radioactive material is in the air, the chamber will also be subject to α rays. Figure 2 shows the shape of the recorded curves to be expected under these two conditions, making allowances for the difference in sensitivity of the chamber to α rays and to β and γ rays. There is considerable uncertainty in fitting these curves to the observed data. Either curve can be made to fit the data of May 26 and July 1 fairly well, so a critical test is not possible from these data. One of the chief difficulties of this fitting is that the radioactive element is not introduced instantaneously but is being brought in for some time. This will cause a slower rise of the curve and a general broadening of the maximum, which is observed.

The curve for August 27 is more irregular, with two periods of sudden decrease in ionization. It is impossible to explain this on the assumption that the radioactive material was on the ground, for the decay rate is much too fast to be due to decay of radium B and radium C. Apparently the radioactive material was being removed during these periods. This therefore suggests that it was

located in the air, and that on this day the air was very inhomogeneous in radioactive content. There was a variable wind with several sudden changes in direction that day. These, however, do not correlate well with the rapid changes in ionization.

It is interesting to note that the first sudden decrease in ionization was coincident with a sharp fall of hail. However it is difficult to see how this could remove radioactive material from the air. This was probably coincident with the meteorological change which caused the removal of the radioactive material.

During the period 17^h20^m to 19^h00^m on August 27, thick walls were used on the ionization chamber, so that ionization during this period was due only to β and γ rays. It was hoped that some indications of the mechanism involved could be obtained from this, but the record is so disturbed by other agencies, that little of value can be determined from it. It does, however, indicate that most of the additional ionization is due to β and γ rays, and precludes the interpretation that the sharp maximum on this day was due to the introduction of radium A into the air.

Conclusions--These results may be summarized by saying that rain associated with a thunderstorm often introduces into the air a radioactive material which appears to be radium B. The additional ionization due to this can be as much as four times the normal ionization of the atmosphere. The seat of operation of this additional ionization is probably the air rather than the ground.

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CORRELATION OF CORONAL AND GEOMAGNETIC OBSERVATIONS, 1944-1946

J. V. Lincoln and A. H. Shapley

Abstract--Observations of the solar corona in 1944-1946 are analyzed with reference to geomagnetic disturbance, extending an earlier investigation by SHAPLEY and ROBERTS [1946] for the period 1942-1944. Coronagraphic data from Climax are now supplemented by observations from two European observatories. The intensity scales of the green emission-line of the coronal spectrum at the three observatories are intercompared, and the regions of activity in the corona are identified from the combined observations. The coronal-geomagnetic correlation has become weaker since minimum epoch of the sunspot cycle in 1944 and the apparent time relationship has shifted.

The intensity of the green line of the coronal spectrum has served as one measure of solar activity in the application of solar-terrestrial relationships to forecasts of geomagnetic disturbance. Analysis of the coronal and geomagnetic observations from August 1942 to July 1944 [SHAPLEY and ROBERTS, 1946] indicated that a systematic correlation existed during that interval, although these early coronal observations were admittedly rough and incomplete. Some of the same types of analyses are now applied to the observations of 1944 to 1946. The observational material differs in that the present work includes in addition to data obtained at Climax (U. S. A.), the observations made at coronal observatories at Pic-du-Midi (France) and Wendelstein (Germany). W. O. Roberts is responsible for the Climax observations, supplied to CRPL under contract [ROBERTS, SHAPLEY, and HODDER, 1945] [ROBERTS and SHAPLEY, 1948]. The data from B. Lyot at Pic-du-Midi are communicated by the Service de Prévision Ionosphérique Marine, while the observations obtained at Wendelstein, many of them made under guidance of K. O. Kiepenheuer, are communicated by the U. S. Signal Corps.

With data from three stations available, we have a more nearly complete series of observations, an average of 215 per year, compared to 141 per year in the earlier analysis of Climax data alone. However, the scales of intensity at each station differ: Climax and Wendelstein use arbitrary scales, and at Pic-du-Midi intensities are measured in millionths of the intensity of the continuous spectrum of the center of the solar disk at λ 5303. The reduction of all observations to a common scale was carried out by comparing the observations at five degree intervals of position angle on observing days common to a pair of sources. Each calendar year was treated separately and all observations were given equal weight. The least squares equation relating the common observations was computed by minimizing the normal deviates on the assumption that errors of measurement were equally likely in each set. Inasmuch as the Climax data are more complete than those available for the European stations, the scale of the Climax observations has been adopted as standard. This is done with the realization that the scale is arbitrary and regulated by inadequate photometric procedures [SHAPLEY and ROBERTS, 1946, appendix]. However, little is known of the photometric methods controlling the Wendelstein arbitrary scale of intensity. Since only 20 observing days are common to Pic-du-Midi and Wendelstein, the relatively reliable Pic-du-Midi scale cannot be used as standard.

The computations give the following linear relations for each of the years 1944, 1945, and 1946, where the numbers in parentheses refer respectively to the number of common observing days and the total number of common observations (C = Climax, P = Pic-du-Midi, W = Wendelstein):

1944	C = 1.1 + 0.21 P	(6; 71)
1945	C = 1.2 + 0.25 P	(14; 341)
1946	C = 2.1 + 0.24 P	(13; 413)
1944	C = 0.3 + 0.64 W	(52; 589)
1945	C = 0.8 + 0.77 W	(76;2113)
1946	C = 2.7 + 1.10 W	(51;1940)
1944	W = 1.5 + 0.42 P	(6; 107)
1945	W = 2.5 + 0.58 P	(8; 320)
1946	W = - 0.8 + 0.25 P	(6; 261)

The last set of equations can be used to check the consistency of the first two. Thus in 1946, if P = 100, C = 26.1, if calculated directly, and 29.3, if converted first to Wendelstein units and then to Climax units. The discrepancies, especially large for 1945, arise because of sampling errors. Therefore, we must acknowledge that our data are limited, and accept errors of this magnitude. The last set of equations do not indicate that the equation W = 0.2 P by the Bureau Ionosphéreque Français [SPIM-O, 1947] is valid for the earlier years.

It is evident that the relationship between the Climax and Wendelstein scales changed significantly between 1944 and 1946. This may be attributed to a change in photometric standards at one observatory or both, or to a non-linear relation between the scales, the latter because the mean intensity of the coronal line was much larger in the pre-maximum year 1946 than in 1944, the minimum year of the sunspot cycle. The constants of the equations relating Climax and Pic-du-Midi scales agree so well for the three years that a mean equation was used to adjust the Pic-du-Midi observations, C = 1.6 + 0.24 P. The Wendelstein and Pic-du-Midi regression equations, based on very few data, were as variable from one year to the next as those for Climax and Wendelstein. In the absence of details on the control of the Wendelstein scale, we must tentatively conclude that the Wendelstein scale is the least stable of the three during the period considered.

Graphs of the daily maximum intensity in each of the four quadrants of the solar limb were constructed from the reduced observations of the three observatories for the years 1944-1946. As an illustration, Figure 1 represents the east limb, north and south latitudes, for the second half of 1946. The approximate heliographic latitude of each daily maximum is represented in the top graph. The period was chosen to demonstrate instances of good agreement among observatories, such as about July 10 and September 20 in north latitudes, and of discrepant observations like those about August 5 and September 25 in south latitudes. The gaps in the observations in November and December are typical of the winter and early spring seasons, when the observing conditions and schedules of these three observatories are erratic.

If we assume that true changes in the intensity of an intense emission region of the corona are slow, a matter of weeks rather than days, then graphs like Figure 1 identify the nominal longitude and latitude of the regions of intense coronal emission comparable to the familiar centers of activity observed with the spectrohelioscope. Assuming that the corona rotates with about the period of the photosphere, we can estimate that the well-determined bright coronal regions extend for 30° to 50° in longitude. The extension in latitude, determined from the distribution of intensity at the limb on individual days, is of the order of 20°. That the coronal regions evolve slowly is shown in Figure 2b which shows graphically their intensity at intervals of the approximate solar rotation period. Most bright coronal regions persisted through more than two rotations. The extent of coronal regions is also evident in Kiepenheuer's drawing [KIEPENHEUER, 1947a].

Twenty-seven-day recurrence patterns of geomagnetic and coronal activity for 1944-1946 are also compared in Figure 2. The former is represented by the daily sum of the three-hourly magnetic character figures K_A, the latter by the maximum intensity observed at the east limb, Climax observations only. The gaps in the coronal data were filled wherever possible by the use of west limb data 14 days before or after the date in question or by interpolation between dates separated by only one day; otherwise the days of no observation are indicated by X in the diagram. Recurrence tendencies in this type of diagram, patterned after BARTELS [1932] are shown by vertical patterns, while the duration of periods of high or low activity are indicated by the horizontal patterns. WALDMEIER [1946] has used this method to compare magnetic disturbance with centers of prominence activity.

From Figure 2 it will be noted that recurrence of magnetic disturbance was weaker in 1945 and 1946 than in the sunspot minimum year of 1944. This is in accord with findings during earlier sunspot cycles [SHAPLEY, 1947]. A substantial increase has occurred in the intensity of the corona since sunspot minimum epoch. Intensities which were significantly above the mean in 1944 were average intensities by 1946. Thus the criterion for an unusually bright coronal region must be changed from year to year. In the early part of 1946 there were two persistent bright coronal regions at the east limb centered at about days 12 and 27. There were also two belts, although less pronounced, of relatively high magnetic activity at about days 15-16 and 26. The coronal regions are not identified exactly enough to determine any general relationships which might exist between magnetic and coronal activity, but the evidence appears to support the conclusion from the earlier coronal data that the number of bright coronal regions is about the same as the number of storm sequences.

From graphs like Figure 1, we selected the dates of east limb passage of well-defined coronal regions whose maximum intensity is above the significance level for each calendar year.

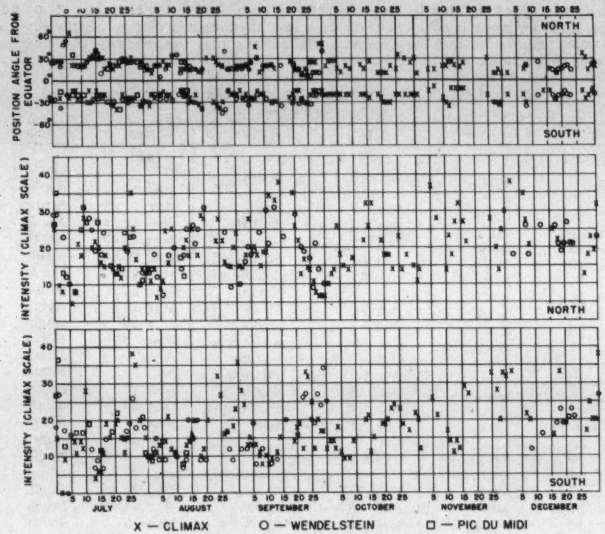

Fig. 1--Daily record of maximum intensity, coronal green line, July - December 1946

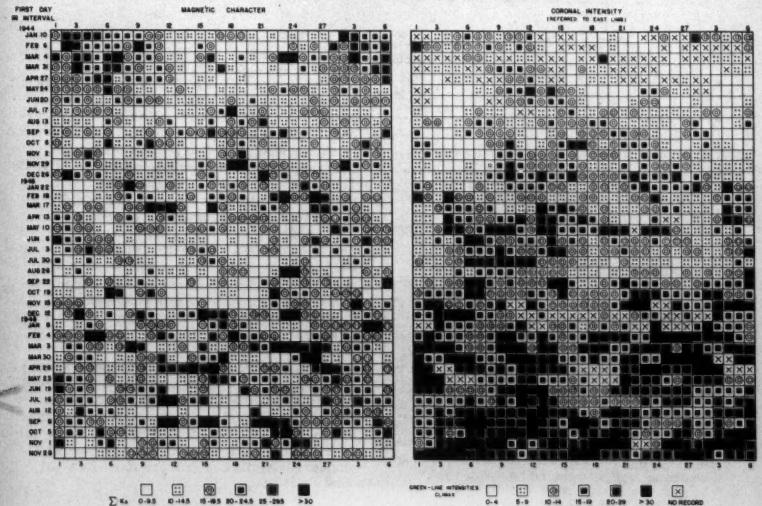

Fig. 2--27-day recurrence diagram of coronal and magnetic activity, 1944-1946

These dates are listed in Table 1. Magnetic activity, measured by the character figure 20 C_A, was examined from three days before to 15 days after these chosen dates using the superposed epoch method. Figure 3 shows the mean magnetic activity after limb passage of the coronal region compared with the mean magnetic activity for the entire calendar year.

Table 1--East limb passage dates of regions with significantly intense coronal emission

Date	Latitude	Date	Latitude	Date	Latitude
1944		1945		1946	
Jan. 8	South	June 2	South		
Feb. 6	South	June 11	South	Apr. 24	North
July 3	South	June 13	North	Apr. 25	South
Aug. 1	South	July 10	South	May 19	North
Aug. 20	South	July 11	North	June 12	North
Aug. 26	South	July 16	South	June 20	South
Oct. 15	South	July 23	South	June 29	North
Oct. 20	North	Aug. 6	North	June 30	South
Oct. 21	South	Aug. 6	South	July 10	North
Oct. 28	South	Aug. 31	South	July 26	North
Nov. 3	North	Sep. 3	North	Aug. 9	North
Nov. 11	South	Oct. 1	North	Aug. 16	North
Dec. 13	North	Oct. 6	South	Aug. 21	North
Dec. 15	South	Oct. 13	North	Aug. 23	South
		Oct. 24	North	Aug. 31	South
1945		Dec. 6	South	Sep. 4	North
				Sep. 14	North
Jan. 9	North	1946		Sep. 18	North
Jan. 18	North			Sep. 23	South
Feb. 13	North	Feb. 27	North	Oct. 15	North
Feb. 15	South	Mar. 19	South	Nov. 14	North
Mar. 13	North	Mar. 20	North	Nov. 16	South
Mar. 21	South	Mar. 27	North	Nov. 30	South
Apr. 29	South	Apr. 11	South	Dec. 2	North

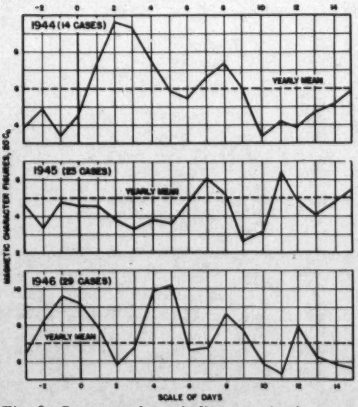

Fig. 3--Superposed epoch diagram showing magnetic activity with reference to day when bright coronal region centered on east limb

The data for 1944 bring out the general characteristics of the relationship found in the analysis of the coronal observations at sunspot minimum [SHAPLEY and ROBERTS, 1946], namely, a pronounced increase in magnetic activity two to three days after the bright coronal region was centered on east limb and also a minor increase eight days after east limb passage. The results are inconclusive in 1945: The slight increases of magnetic activity above the yearly mean at seven and again at 11 days are probably not significant. In 1946 a perhaps more consistent coronal-magnetic correlation obtained. Magnetic activity was greatest, on the average, at four to five days after east limb passage of the selected coronal regions, although activity was also high at -1 and 0 days. Secondary maxima appear at eight and 12 days.

The significance of a relationship demonstrated by a superposed epoch analysis cannot be evaluated directly with simple statistics. The values of 20 C_A, which are combined in each point of the graphs of Figure 3, range in nearly all cases from 0 to 14 or more. The standard deviations run from about four to

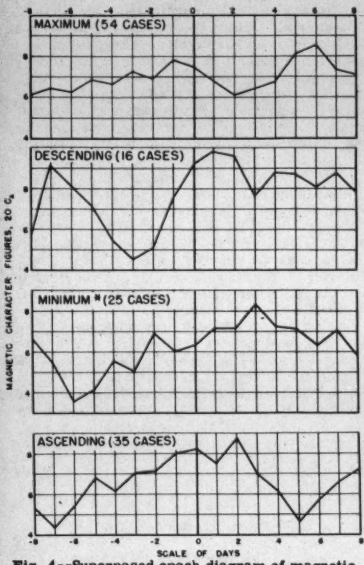

Fig. 4--Superposed epoch diagram of magnetic activity with reference to meridian passage of sunspots ≥1000 millionths at four stages of sunspot cycle, 1890-1936(* includes spots ≥ 500 millionths)

ten units, and in the majority of instances exceed the value of the mean. Thus the variations indicated by the superposed epoch graphs are not significant according to the criteria established for simple regression problems. To properly test the significance of the variations, other and more involved considerations must be taken into account. We reject on physical grounds the interpretation that the graphs demonstrate that the intensity of magnetic disturbance is a continuous function of the longitude from the central solar meridian of the bright coronal regions. Our purpose is to investigate whether there is a preferred location of the coronal regions at the time of magnetic storms. And since magnetic storms do not follow a regular pattern of intensity and duration, a quantitative measure of the distribution of character figures has little meaning.

In general, one suspects that the variations shown in a superposed epoch diagram are real if (1) the same relationship, or time lag, is obtained in each of two or more arbitrarily chosen samples of the data, and (2) the variation curve is more or less smooth. Applying these rough criteria to the coronal-magnetic relationship over the 4 1/2 years for which systematic coronal observations are available, we consider that the evidence is not conclusive. The relationships for 1942 (second half), 1943, and 1944 are similar, and differ from those for both 1945 and 1946. The apparent time lag is variable. The curves for 1942, 1943, and 1944 are relatively smooth, and the likelihood of a real relationship thereby enhanced. The diagram for 1945 is not smooth, while the mean curve for 1946 shows consistent changes in successive days after the epoch, except for day 12. On this basis, the relationship shown for 1946 again has relatively high significance.

However, it must be remembered that magnetic character figures are a highly conservative time series, and that the mean curve obtained from randomly selected epochs would still tend to be smooth. Thus, if the variations shown in Figure 3 and in Figures 3 and 4 of the earlier analysis [SHAPLEY and ROBERTS, 1946] are real, the time lag between east-limb passage of the selected coronal region and related magnetic activity varies with the stage of the sunspot cycle. Then we will have to have coronal data for at least a sunspot cycle before we can be sure of the relationships shown by this type of analysis. Other solar-geomagnetic relationships appear to change with the stage of the sunspot cycle, including the correlation of meridian passage of large sunspots and magnetic activity represented in Figure 4. The selected dates for these superposed epoch diagrams are the meridian passage dates of sunspots with area ≥ 1000 millionths of the Sun's visible hemisphere as reported in the Greenwich publications for the years 1890-1936. In the minimum years only four spots this large were observed; therefore those with area ≥ 500 millionths have been included. The magnetic data used were the international magnetic character figures. The meridian passage relationship of the maximum years (the calendar year of maximum epoch ± one year) is less evident than at the other stages of the cycle.

There is little resemblance between Figure 3 and Figure 4, c and d. If the sample of the coronal data since 1942 is representative, we can conclude that corona and sunspots are different manifestations of solar activity. This is borne out by detailed examination of the interval 1944-1946. Of the 32 largest sunspots with area greater than ten square degrees, only three were within seven degrees of longitude of the center of a bright coronal region while 14 were within 25°. Observations were incomplete in some of the remaining cases; in others, the large sunspot was probably associated with a coronal region of minor importance according to the criteria used in this paper. Apparently the size of a sunspot bears little relation to the intensity of the corona above it.

Our method of selecting the epochs in the present analysis differs slightly from that in the analysis of the early Climax data. Here we have attempted to identify the longitude of the center of the region of significant coronal activity, since the non-systematic errors of observation at the three stations made it impossible to employ the earlier selection method of using the date of first appearance of significantly intense corona at the limb. Thus the present results should be compared with Figure 13 of the earlier paper, rather than with Figure 12. It is also noted that bright corona is present on the visible disk of the Sun at -1 and even -2 days before the selected date of limb passage because of the 30-50° dispersion in longitude of the coronal region mentioned above. Thus the magnetic activity at -1 days in the superposed epoch diagram for May 1946 may not be trivial.

Superposed epoch analyses are very useful to identify the time relationship between solar and geophysical phenomena. We have not gone as far as we would like in evaluation of the significance of the trends or relationships. But the potentialities of the data are limited. For both the coronal and magnetic data, the observations on one day are affected by the observations of the days previous, that is, the measurements on successive days are not independent. Further, the agreement among observers of the corona is at best rough. The correlation between observations of the intensity of the corona at Climax and Pic-du-Midi in the period under consideration is, for example, about $r = +0.62$. The disparity in the observations is such that the location of the brightest part of coronal regions is frequently in doubt by one or sometimes even two days. Especially where there are gaps in the observations, it is hard to make the decision as to whether a coronal region is significantly bright. The best first approximation seemed to be to accept, as was done in this analysis, only the positively identified coronal regions for inclusion in the superposed epoch analysis. Observational errors are evidently large; KIEPENHEUER [1947b] estimates that the Wendelstein observations may be in error by 20 per cent. The discrepancy of measurement by two observers, both at Climax, averages about ten per cent. Until such errors are reduced by improvements in observational technique, we can only estimate the relative significance of the relationships shown.

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ADJUSTMENT OF BIKINI ATOLL TO OCEAN WAVES

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(Contribution from the Scripps Institution of Oceanography, New Series, No. 392)

Abstract--Atolls in the trade-wind belt withstand a continuous heavy pounding from ocean waves. Against the windward side of Bikini Atoll alone it is estimated that waves dissipate 500,000 hp, one-fourth the power generated at Hoover (Boulder) Dam. To withstand these forces the exposed reefs are moulded into a most effective natural breakwater, consisting of long narrow grooves in the seaward face of the reef, and surge channels on the reef flat. These surge channels are tuned to the prevailing wave periods. Their distribution around the reef conforms to the distribution in wave activity, which in turn is controlled by prevailing winds over the North and South Equatorial Pacific.

Some of the power of the breaking waves is utilized to maintain a water level just inside the surf zone about 1.5 ft above the general sea level. The water flows downhill over the reef into the lagoon, regardless of the stage of the tide, with an average speed of 0.5 to 1.0 knot, but occasionally with speeds up to four knots. The reef as a biological community utilizes this current and maintains thereby a wave-resisting and modifying structure.

Grooves and surge channels--The features to be described here are best developed between Bikini and Amen Islands (see Fig. 1), where the reef is directly exposed to the waves of the prevailing trade winds [EMERY, TRACEY, and LADD, in press]. Grooves cut the seaward face of the reef at fairly regular intervals (see Fig. 2) and give it the appearance of a series of buttresses rising from the debris-covered slope of the atoll.

The grooves commence at a depth of 50 to 75 ft, then run steeply up the reef slope into and through the surf zone. At the inner end, they may end abruptly or be continued as surge channels, or as tunnels, with blowholes, under the reef platform. Just inside the surf zone, around the blowholes and the heads of grooves and channels, nullipores and coral colonies rise about two ft above the general reef level. The upper faces of the buttresses are paved with living nullipores which present an extremely rough surface. The sides of the grooves are covered with projecting, often bracket-like, colonies. The bottoms of the grooves consist of relatively smooth rock and sand.

Between Bikini and Amen Islands the grooves are spaced about 25 ft apart, are about 16 ft deep at their inner ends, and vary in width from three to six ft. The grooves play a vital part in the function of the coral reef as a breakwater. Near their outer ends, which extend to the maximum depth of appreciable wave action (see Appendix 1), they interfere with the normal orbital water motion associated with waves on a sloping bottom, by taking the bottom out from under the waves; at the inner end they pursue a divide and conquer policy. The resulting effect on waves is remarkable. To an observer standing on the platform just inside the surf zone, the breakers appear to come crashing down upon him; two sec later, the wave has virtually disappeared, its momentum converted into a noisy surge which rushes up the channels on each side of the platform. Much of the remaining energy is spent when the surge meets the backrush from the preceding breaker. Wave energy is also dissipated by friction along the sides of the grooves and channels, where an abundant bracket-like growth of organisms is found.

The surge channels are properly tuned to the average wave characteristics (see Fig. 2). An average depth of 15 to 20 ft, and a length of about 200 ft (ℓ_1 in Fig. 2) between the outer end of the platform (Lithothamnion ridge) and the inner ends of the channels correspond to a fundamental period of oscillation of eight sec, which is also the prevailing period of the waves of the trade winds (see Appendix 2). As a result, the uprush of each wave will meet the backrush of the preceding wave at approximately mid-channel.

Distribution of grooves and prevailing wave directions--The dimensions of grooves around the entire reef of Bikini Atoll were estimated from aerial photographs, and are designated by arrows on Figure 1. The spacing s, width w, and outer length ℓ_0 (see Fig. 2) of the grooves are designated by the spacing, width, and length of the arrows. Photographs of the reef to the south of Bikini Island were unsuitable for the determination of the grooves, but it is known that grooves are well developed in that area.

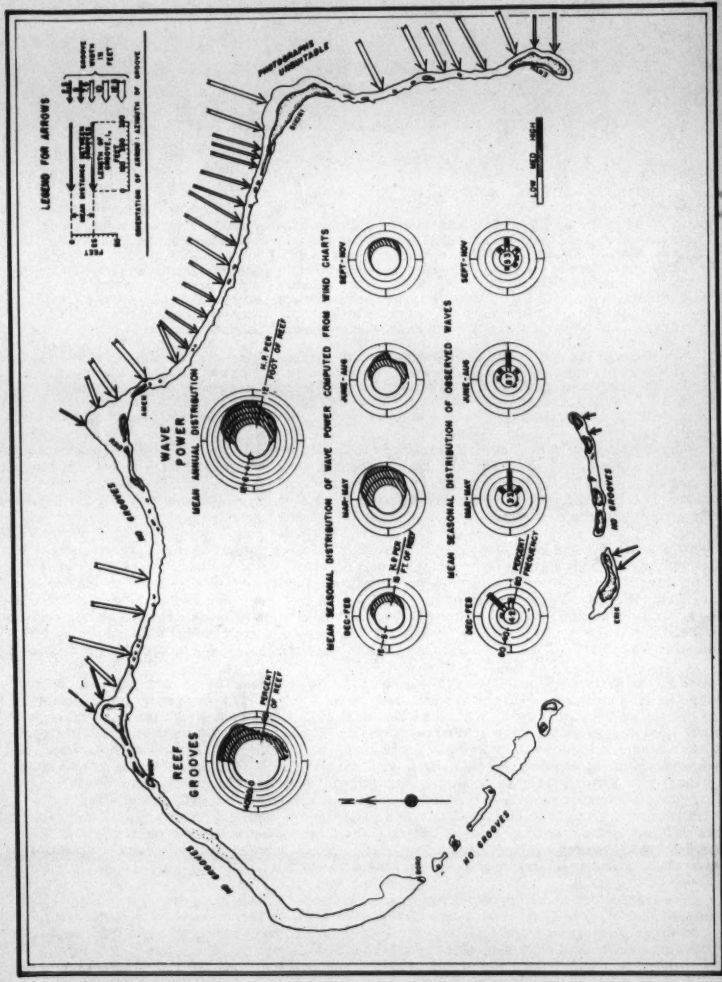

Fig. 1--Distribution of reef grooves and wave power around the reef of Bikini Atoll; the length, width, and spacing of the grooves are proportional to the length, width, and spacing of the arrows drawn against the reef; polar coordinate graph to the left shows per cent of area occupied by grooves as function of their exposure; polar coordinate graphs to the right show mean distribution of computed wave power, and of observed waves

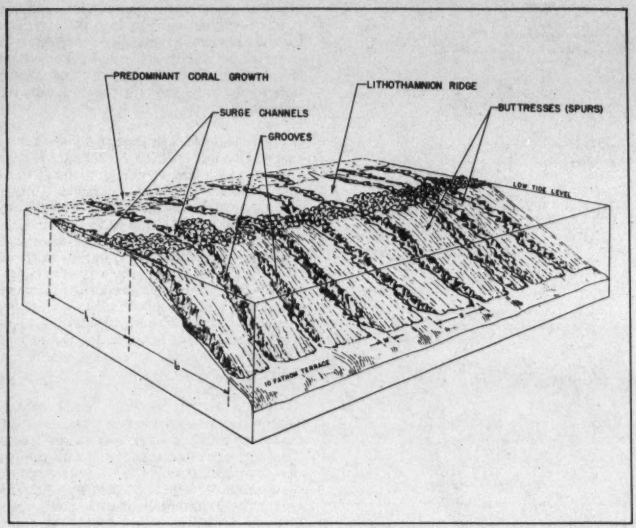

Fig. 2--Generalized sketch of seaward face and top of reef on windward side of Bikini Atoll; original by D. B. Sayner

The greater length of the grooves with northern exposure relative to those with southern exposure is due to the steeper slope of the reef to the south [EMERY, TRACEY, and LADD, in press]. The absolute depth at which the grooves commence appears to be approximately constant, and to extend to the greatest depth for which wave action is appreciable (see Appendix 1).

The per cent of reef area occupied by the grooves equals 100 w/s. This is plotted as a function of the azimuth of the grooves on the polar coordinate graph on the left in Figure 1. No grooves were found where the reef exposure has a westerly component.

The distribution of grooves can be correlated with the distribution of wave power around the Atoll. The polar coordinate graphs to the right in Figure 1 give the average seasonal and annual distribution of wave power plotted against reef exposure and expressed in units of hp per foot length of reef.

Wave power was computed in the following manner. The principal generating areas were determined from the Atlas of Climatic Charts of the Oceans [UNITED STATES WEATHER BUREAU, 1938]; they fall into the trade-wind belts of the North and South Pacific. (Swell from the "roaring forties" may occasionally reach the northern Marshalls, but will be too low to be significant.) The frequencies of the prevailing winds in the two main generating areas, and of winds from other directions, were determined from wind roses on the North and South Pacific Pilot Charts. The height, period, and direction of waves reaching Bikini from all directions were then computed, following the method for forecasting sea and swell from weather maps [SVERDRUP and MUNK, 1946a]. Finally the bending of waves around the Atoll due to refraction was estimated [SVERDRUP and MUNK, 1946b] and the wave power computed (see Appendix 3).

A rough check of the validity of these computations could be obtained from sea and swell observations appearing in the Sea and Swell Charts, Northwestern Pacific (Hydrographic Office 10712C). Averages were formed for each season, taking into account all observations in the area between longitudes 160°E to 170°E, and between latitudes 5°N to 15°N. These are presented by the wave roses in Figure 1. The main features in the observed wave distribution are in agreement with the computed distribution of wave power.

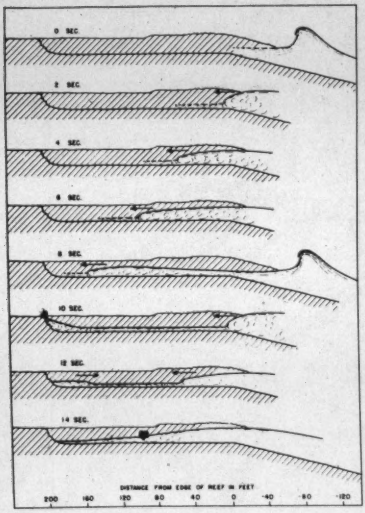

Fig. 3--Breaking wave produces surge which travels up the surge channels, is reflected on the upper end, and meets surge from subsequent breaker mid-channel; surge channels are tuned to the period of prevailing waves

The graph of the annual distribution of wave power is based entirely upon the computed rather than the observed wave characteristics, partly because of the small number of observations, but chiefly because the quality of these observations is believed to be inferior to the quality of the computed values.

The diagrams in Figure 1 show a significant correlation between the directional distribution of wave power and of reef grooves. Grooves are restricted to reefs with a component of exposure to the east, the direction from which wave action is pronounced. Due to wave refraction a small portion of the wave power does reach the western sides of the Atoll, but there the power dissipated amounts to only a fractional hp per foot length of reef, and it appears that at least one or two hp is required for the development of grooves. On the eastern half of the reef the average power delivered by the waves equals three hp per foot length of reef, or about 20 hp per groove.

The distribution of grooves reveals a maximum for an east-northeast exposure, and a secondary maximum for southeast exposure. These features are associated with the principal wave-generating areas in the trade-wind belts of the North Pacific and South Pacific, respectively. The distribution of wave power reveals the same features; except during the summer months the effect of the distant South Pacific trade winds is overshadowed by the effect of the local trade winds. For a corresponding location in southern latitudes the reverse should be true, and the distribution should be a mirror image of the one found at Bikini.

The bimodal distribution of grooves points strongly toward a wave origin; if the channels were to be attributed to direct wind action, the development in the southeast quarter would be missing.

Head of water at reef edge--Not all the energy of the incoming waves is dissipated by friction. Some energy is converted into potential energy to maintain a water level at the outer edge of the reef at about two ft above the mean water level of the ocean and lagoon water. If the entire wave energy were to be consumed in lifting the water which flows over the reef, the level of this volume of water could be maintained 42 ft above the mean sea level (see Appendix 3). Therefore only about 5 per cent of the wave's energy is utilized to raise the water level, and 95 per cent is dissipated by friction, a large part of it within the surge channels.

It may be worthwhile to consider the design of artificial breakwaters along the lines of the natural coral reef breakwater, as the present structure of these reefs represents the result of thousands of years of adaptation resulting in a most suitable structure to withstand the wave forces. Artificial surge channels have indeed been employed on the south coast of the Mediterranean in the generation of electricity by means of wave power. These channels were relatively wide at their outer end and converged gradually toward the inner end. In this manner the water level in a reservoir was maintained at an average elevation of 40 ft above the mean sea level.

Wave-driven currents over the reef--From the region of maximum elevation the current flows into the lagoon under the influence of gravity assisted by wind traction. Between Bikini and Amen Islands, the speed is about one ft/sec; except during spring low tides, when the retarding effect of bottom friction is disproportionally large, this speed is remarkably independent of tide. In the presence of obstructions the wave-driven current may give rise to striking features. For example, a few days after the arrival of the USS Bowditch a 100-ft channel broke through the sandspit at the northwest end of Bikini Island, and water flowed through this channel in a steady stream for almost six months.

Currents over the reef were measured by dropping dye bombs from planes, and taking timed photographs of the drifting color patches [VON ARX, 1948]. Between February and April 1946, while the trade winds blew predominantly from the east-northeast, wave-driven currents flowed into the lagoon over the entire eastern and northern reefs, adding 3×10^{14} cm^3 of water, one per cent of the entire lagoon volume, during each 12-hourly interval. During an equal time interval the tidal flow (chiefly through the deep southwesterly passages) amounted to two per cent of the lagoon volume. Although the oscillating tidal current represented the principal component of water exchange between the ocean and the lagoon, the one-directional wave-driven current is of primary importance to the renewal of water in the lagoon. The latter feature was of interest with regard to the flushing of the lagoon of radioactive water.

The wave-driven current is important also for another reason. At noon, expecially during low tide, the water over the reef becomes warmer, more saline, and supersaturated with oxygen. Upon entering the lagoon, this "reef water" may be recognized as a distinct water type. The mixing of this water with the lagoon water provided a method for computing the rate of vertical diffusion [MUNK, EWING, and REVELLE, in press].

Discussion and conclusions--Waves breaking over coral reefs may lead to the formation of grooves and to the flow of currents over the reef. The only other known examples of currents due to wave action are longshore currents and rip currents caused by waves breaking on gently sloping beaches [MUNK and TRAYLOR, 1947]. Since the waves represent an integrated effect of the winds, their energy being accumulated during many hours, and over thousands of miles, a wave-driven current assures a steadier supply of water than a wind-driven current.

The waves and the wave-driven current may be of biological significance in three ways. First, they limit luxuriant growth of Lithothamnion and other encrusting coralline algae to situations exposed to the heaviest wave action, possibly because such action prevents the establishment of sedentary organisms. Secondly, the current maintains a nearly constant supply of mineral nutrients and dissolved gases over the whole width of the reef. Thirdly, as noted above, the current carries water into the lagoon, which at noon is supersaturated with oxygen. Also, on the basis of evidence presented elsewhere [SARGENT and AUSTIN, in press], it is believed that there is a net transport of organic matter into the lagoon which is of importance in the total organic matter budget of the lagoon.

Appendix 1

This work represents results of research carried out for the Hydrographic Office, the Office of Naval Research, and the Bureau of Ships of the Navy Department under contract with the University of California. The original of Figure 2 was drawn by D. B. Sayner.

Depth of wave action--The average speed of water movement along the bottom in water of depth h is given by

$$u = 2\pi H/T \sinh^{-1}(2\pi h/L) \quad (1)$$

where H and T are the height and period of the wave responsible for the water movement. The wave length is given by

$$L = (gT^2/2\pi) \tanh(2\pi h/L) \quad (2)$$

where g is the acceleration due to gravity. For a wind speed of 16 knots, blowing over a long fetch and for a long time, the wave height and period equal seven ft and eight sec, respectively [SVERDRUP and MUNK, 1946a]. These figures are in agreement with the observed dimensions of trade-wind waves. Simultaneous solution of (1) and (2) leads to the numerical values shown in Table 1.

Table 1--Mean orbital speed on the ocean bottom

Depth h	Speed u	Size of particles which can be eroded
ft	ft/sec	mm
50	1.2	3
75	0.8	1
100	0.5	0.05
125	0.32	No erosion

The outer ends of the grooves fall into a depth of about 75 ft, where the average speed due to wave action is about 0.8 ft/sec. The third column shows the size of particles which can be eroded by a current of speed u, based upon measurements in rivers by Hjulström [TRASK, 1939, pp. 10-11]. According to Hjulström, "...fine sand, which has a diameter of 0.3 to 0.6 mm, is the easiest to erode, whereas both silt and clay on the one hand and coarse

sand and gravel on the other require higher velocities." If these conclusions are applicable here, they indicate that no erosion can take place for current speeds less than 0.5 ft/sec, that is, at depths exceeding 100 ft, no matter how small the size of the grains.

Appendix 2

At the depth of 75 ft the reef slope is relatively gentle, forming virtually a terrace [EMERY, TRACEY, and LADD, in press]. One would be tempted to ascribe this "ten-fathom terrace" to wave action, were it not for the fact that it is also found inside the lagoon.

Table 2--Length of channels for maximum interference

Period T	Length l_2
sec	ft
6	130
8	175
10	220

Dimensions of surge channels--The speed of a surge in a channel equals approximately $\sqrt{gh}$, where h is the depth of the water measured from the highest point in the surge. For effective interference the surge must travel a distance of roughly the length of the channel during one wave period (see Fig. 3). The corresponding length of the channel equals approximately $T\sqrt{gh}$. Setting $g = 32.2$ ft/sec^2, $h = 15$ ft, leads to the values shown in Table 2.

Appendix 3

The wave period in the region of the northern Marshalls is remarkably constant and falls within the limits of seven to nine sec, probably more than 90 per cent of the time. Over most ocean areas the period of the significant waves vary between such wide limits (probably six to 14 sec) that resonance for any permanent structure would be achieved only a small fraction of the time.

Wave power--The mean energy dissipated by the waves each sec against a unit width of reef is $(1/32\pi)\rho g^2H^2T$ where ρ is the density of water. The transport of water per ft width of reef equals h' V where h' is the depth of water over the reef, V the corresponding speed of flow. If the entire wave energy were to be utilized in raising the water flowing over the reef, then

$$(1/32\pi)\rho g^2H^2T = \rho g\, h'Vs \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

so that the vertical distance through which the water would be raised is

$$s = gH^2T/32\pi h'V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Setting H = 7 ft, T = 8 sec, h' = 3 ft, V = 1 ft/sec gives s = 42 ft.

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THE CIRCULATION SYSTEMS OF BIKINI AND RONGELAP LAGOONS

William S. von Arx

(Contribution No. 421 of the Woods Hole Oceanographic Institution)

Abstract--Four and one-half months of the early part of 1946 were spent in the field at Bikini and Rongelap Atolls to study the circulation systems within the lagoons. Additional synoptic studies were made in the laboratory of kinematically similar models based on early field data. The results of these studies were later tested against further observations made in the field. It was found that both lagoons exhibited a primary circulation (overturning wind-driven circulation) and a secondary circulation (rotary circulation composed of two counter-rotating compartments). The direction of the primary circulation and the division between the counter-rotating compartments of the secondary circulation were always contained in a vertical plane having roughly the azimuth of the prevailing wind. The vigor of both circulations varied with the average wind strength taken over the previous 24 hours. Perturbations of the primary and secondary modes of circulation were produced by tides, waves, and the North Equatorial Current which surrounds the atolls of the northern Marshall Islands group. Seasonal changes were also noted; the circulation of the winter months when the northeast trade-winds prevail showed a marked stability and strength which was lacking in the summer season when the atolls are on the edge of the belt of doldrums.

In addition to the qualitative synopsis of the circulations, numerical data are presented in tabular form which show the volumetric exchanges of water between the lagoons and the ocean. An estimate is made of the rates of refreshment and overturning of each lagoon. A chart of the values of eddy diffusion in the surface plane is given for Bikini, as well as secondary data on the behavior of current poles and dye trails in a variety of wind and current strengths.

Introduction--The greater part of the field data for this study was accumulated at Bikini Atoll in the course of four and one-half months residence there. The data from Rongelap Atoll were gathered in the course of only six days. The data are probably more representative than the period of observation suggests, for the work at Rongelap was executed by a relatively large force and planned in the light of the experience gained and techniques used at Bikini. Nevertheless it should be assumed that all generalizations and discussions of principle are based upon observations made at Bikini and apply only to Bikini unless specifically extended to include Rongelap.

Inspection of Table 1 will show that the dimensions of Bikini and Rongelap Lagoons are so large that some means of synthesis is required to relate observations made at separated points.

Table 1--Comparative physical dimensions of Bikini and Rongelap

Specification	Bikini	Rongelap
Approximate volume	5.0 mi^3	8.5 mi^3
Approximate area [NUGENT, 1946, p. 748]	192 mi^2	305 mi^2
Total reef length [NUGENT, 1946, p. 748]	57 mi	80 mi
Length of reef awash	29 mi	53 mi
Length of island strip	13 mi	18 mi
Width of passes and channels	15 mi	9 mi
Average depth of lagoon [NUGENT, 1946, p. 748]	26 fm	28 fm
Average depth over reefs awash	1/2 fm	1/2 fm

Therefore, in addition to field work, two months were spent in the laboratory to develop a technique whereby the observations made in the field could be reproduced in kinematically similar models and the circulations studied synoptically. Two models were built of Bikini on a scale of 1/100,000 and one of Rongelap on a scale of 1/150,000. These were placed separately in a flow tank and subjected to appropriately scaled ocean current, wind, waves, and tide. The behavior of each model was adjusted to resemble its prototype at all the points observed in the field and the resemblance was assumed to hold for all points in between. A total of over 60 points representing more than 160 stations and repeated stations was available for the Bikini models, and 37 single observations were available for the Rongelap model. It is through study of these models and the field data that the selection was made of the most probable circulation hypotheses.

Discussion of results--Four sources of energy have been found to drive the circulation within Bikini and Rongelap Lagoons: Wind, waves, tides, and the North Equatorial Current. Most of the water motion of the lagoons is produced by wind traction on their surfaces. The exchange of lagoon water with that of the sea is accomplished in winter (the trade-wind season) by tides and wave action, and in summer (the doldrum season) by tides and the North Equatorial Current. The change of agencies occurs with the seasonal migration of the northeast trade-wind belt which moves northward in summer, leaving the northern Marshall Islands more or less becalmed in the doldrums. The effect of the presence or absence of the trade-winds is so marked that constant reference to them must be made in order to present the field data and circulation hypotheses intelligibly.

The effect of the active forces is determined as much by the solid physical structures of the atolls as by the forces themselves. Each lagoon is essentially a "lake in mid-ocean," cupped in a shallow saucer-like basin supported by a solitary mountain peak. From a remote vantage point southeast of the atolls they must appear somewhat as shown in Figure 1. The atoll structures rise abruptly from the ocean floor, which in this region lies at a depth of about 2000 fathoms. Between the atolls, and sometimes coalescent with them, there are flat topped seamounts, which HESS [1946] has described and called "guyots." These fail to reach the surface by six or seven hundred fathoms. Both the guyots and atolls obstruct the flow of the North Equatorial Current and

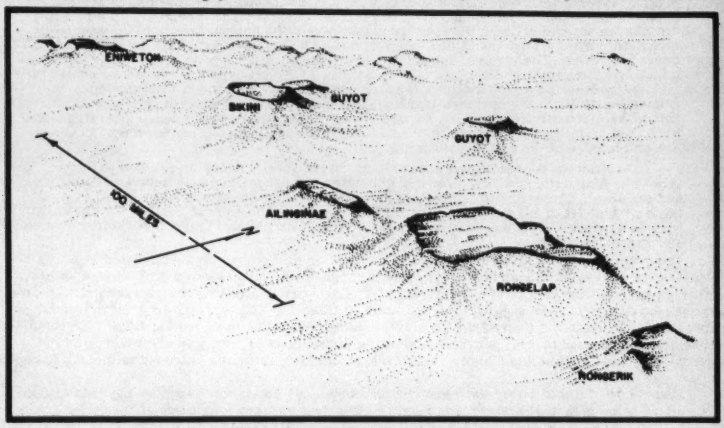

Fig. 1--Rongelap, Bikini, and their surroundings, as they would appear from the southeast with the water removed

confuse its westward motion through the area. Waves and swell also progress westward through the atolls during the trade-wind season and pound systematically on the eastern and northern reefs. As a result of this pounding and the asymmetrical supply of nutrient materials from the sea, the windward reefs are concave upward while the leeward reefs are convex upward.

Along most of the length of the concave windward reefs there is a broad water-filled terrace fenced in by the island strip on the lagoon side and a cavernous bulwark of coral and algae on the seaward side, shown in section in Figure 2. The cavernous structure is honeycombed with rooms connected to the sea by surge channels. Cracks in the arches of the rooms are open to the sky. Swell rammed up the surge channels fills the rooms and forces water upward through the cracks and onto the terrace. The surface of the water on the terrace was measured repeatedly by H. J. Turner at a level 0.5 m higher than the level prevailing in the lagoon. In response to this steady head the terrace water flows between the islands into the lagoon. At Bikini several hundred photographic measurements made with dye bombs dropped on the reef from aircraft show an average inward velocity of flow of nearly 50 cm/sec. The flow is continuous throughout the trade-wind season and supplies approximately one-third of the volume of new water added to the lagoon each day. During the doldrum season, when the ocean swell is much reduced, the inflow becomes negligible or even reversed.

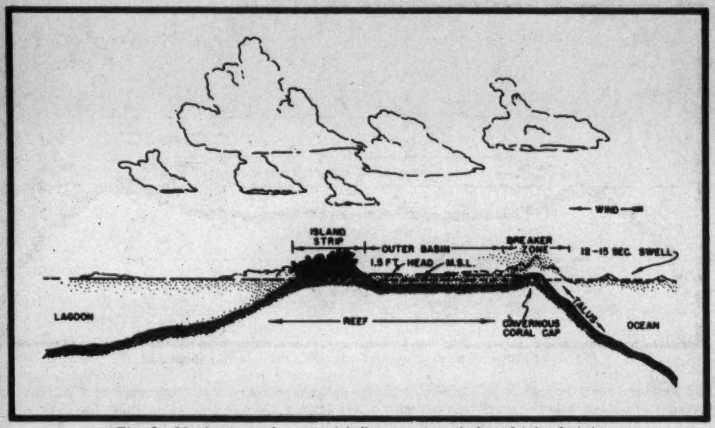

Fig. 2--Mechanism of constant inflow across windward island strip

Over the rounded leeward reefs similar aerial observations of the flow show that the water transport alternates with the tides. The leeward reefs are submerged so that waves cross them, but since leeward waves are those which have been diffracted around the whole atoll, their energy is small and their approach oblique. The water driven by the wind along the surface of the lagoon toward the leeward reefs causes the flow over them to be predominantly seaward. During the doldrum season when the wind-driven surface current moves more slowly the tidal alternations of flow are more symmetrical.

The stress of the wind on the lagoon surfaces moves a layer of water along with it. Well over 100 current measurements at 34 stations at Bikini show the thickness of the surface layer to change with the strength of the wind from five to 20 m and its speed to be very close to three per cent of the average wind speed taken over the previous 12 hr. The thickness of the surface layer in winter is usually 13 m and its average speed is 25 cm/sec. In summer these values drop to an average thickness of nine m and a speed of less than 15 cm/sec.

Throughout both the summer and winter seasons in both lagoons the volume of water transported in the surface current is too great to be exhausted through the leeward passes or over the leeward reefs; consequently some of the water sinks and returns upwind along the bottom as shown in Figure 3. The bottom current is much thicker and slower than the surface current. It links the two ends of the surface current and produces a closed circulation which constitutes the primary overturning circulation system found in both lagoons.

The volume of water transported by the bottom current is somewhat greater than that carried by the surface current. When the bottom current reaches the lee of the windward reefs the water is forced upward. The greater portion finds its way back into the surface current, but a small fraction of the upwelling water diverges in the lee of Bikini Island at Bikini and in the lee of Eniaetok Island at Rongelap and flows in opposite directions along the reef. Measurements made at Bikini show the wind-driven surface layer to be less than two m thick within 3000 m of the lee of islands along the windward reef, and within 2200 m in the lee of open reef. The fetch needed to produce a wind-driven surface current of normal thickness has been arbitrarily chosen as the width of the zone of upwelling. The divergent currents within this zone and their extensions along the reef constitute the secondary circulation system found to exist in both lagoons.

The secondary circulation, shown in Figures 4 and 5, divides the lagoons into two counter-rotating compartments which move in a clockwise sense in the southern portions and in a counter-clockwise sense in the northern portions. Beginning at the line of divergence in the lee of the windward reefs, a longshore current occupying the full depth of the lagoon basin can be traced in either direction. Both currents travel about half the lengths of the lagoons along the northern

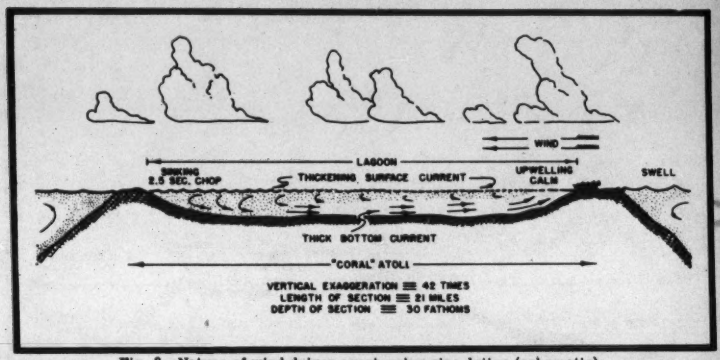

Fig. 3--Nature of wind driven overturning circulation (schematic)

and southern reefs respectively. In each case the longshore current is confronted by a salient in the reef which turns the current into the body of the lagoon. At each of these points the current sinks and becomes part of the bottom current where it is indistinguishable from the primary circulation system.

At Bikini, where this mechanism was discovered, the southern branch of the longshore current crosses the mouth of Enyu Channel. The channel is only 14 m deep so that the bottom current has little chance of access through it to the sea. A current of ocean water sweeps around Enyu Island and enters the lagoon through the eastern third of Enyu Channel at a speed of from 20 to 40 cm/sec. The southbound longshore current heading for the same part of the channel at a speed of 15 cm/sec.is forced upward and westward by the bend of the reef in the lee of Enyu Island and then encounters the incoming ocean water. The result of this encounter is the Enyu spiral, a slowly spiralling stream of water moving westward along the southern reef and islands with a speed of from 20 to 35 cm/sec. The Enyu spiral extends from top to bottom of the lagoon and is about 3000 m wide. In crossing the mouth of Enyu Channel the upper layers are bowed in and out with the changing tide. Part of the stream is split against Arji Island, at the west end of Enyu Channel with a small component escapes into the sea at a rate of 35 to 45 cm/sec. The remainder skirts the intermediate islands, and again encounters the reef at the sill of Rukoji Channel. Here the upper ten m of the stream goes out to sea, and the bottom portion is turned northward by the Rukoji sill, and eventually eastward by the primary circulation, to become part of the normal bottom current. The bottom current is gathered from the western third of the lagoon, but it is not until it is augmented by the remains of the Enyu spiral and its counterpart along the northern reefs, which joins the flow at a point half way between Yuro and Namu Islands, that it assumes its full strength. The interaction of ocean water with lagoon water in the Enyu spiral generally produces water of lower salinity than is found elsewhere in the lagoon.

In summer the Enyu spiral probably ceases to exist, for under the influence of light southeasterly summer winds Enyu Channel becomes a strong source of incoming ocean water. This forces a reorganization of the secondary circulation system.

The flow through the southwest passes and channels is predominantly tidal. Despite the fact that these gaps in the reef are direct openings to the sea in which tidal currents move at speeds sometimes approaching 150 cm/sec, they produce only a small effect upon the lagoon circulation and its refreshment rate. This is due to the fact that the water entering the lagoon on the flood tide through a pass does not get far from the mouth of the pass before the tide changes and draws most of it out again. It is estimated that only 30 per cent of the water entering a pass on the flood tide remains in the lagoon at the completion of the ebb tide. This remainder is the quantity which was moved away from the influence of the pass by the primary lagoon circulation. On the flood tide, currents radiating from the southwestern passes were detected 5000 m inside the lagoon, but not all the water moving in response to the flow in the passes comes through them; hence the radius of direct refreshment around the passes is probably somewhat less than 5000 m.

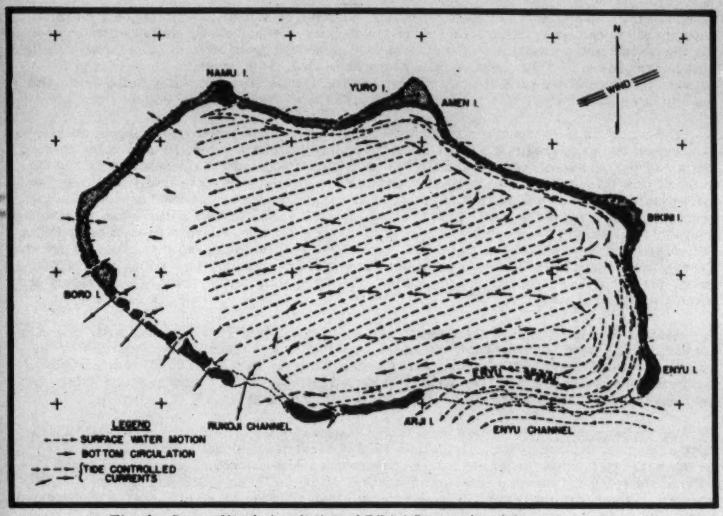

Fig. 4--Generalized circulation of Bikini Lagoon in winter

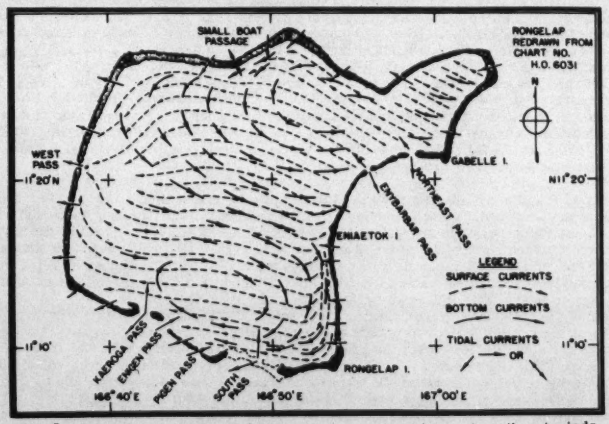

Fig. 5--Generalized circulation of Rongelap Lagoon under east southeast winds

The southwestern passes at Bikini were studied intensively both from the air and from shipboard. It was found that the flow through them was 40 per cent stronger on the ebb tide than on the flood. This condition counteracts in part the continuous inflow of water over the windward reefs in winter and the inflow through Enyu Channel in summer. The current through the passes is hydraulically induced by the difference in level between the ocean and the lagoon. The ocean

rises and falls as a simple harmonic oscillator, but the lagoon level, restricted by the limited capacity of the passes to transport the required volumes and the constant inflow of water over the windward reefs, cannot keep in step. The lagoon surface probably oscillates through a slightly smaller amplitude than the ocean surface and is somewhat out of phase in the vicinity of the passes. The turn of the current in the passes is 25 min later than high water in the ocean and ten min later than low water in the ocean. The duration of slack water is less than two min.

This situation is even more marked at Rongelap because the proportion of lagoon volume to cross-sectional pass area is 3.5 times greater. This results in a larger head of water between the inside and outside of the lagoon during the mid-stage flood and ebb tides, which causes the water to flow much farther into the lagoon and take the form of a jet. Observations of the flow through three of the passes and simultaneous measurements as much as 8000 m inside the lagoon along the jet detected the arrival of the flooding current. Model studies of the same phenomenon indicated the length of the incoming column of the largest jet from Kaeroga Pass to be 10,000 m and water to be pushed ahead of the jet as far as 12,000 m from the pass. It is expected that the Kaeroga jet returns to the sea on the ebb tide considerably less water than would retrace its course through a corresponding pass at Bikini. The South Pass jet is probably more nearly comparable to Bikini passes.

West Pass in the middle of the leeward reef at Rongelap (see Fig. 5) is unusual in that it is constantly outflowing. It is probably one of the principal exits for surface water driven by the wind toward the western side of the lagoon. Current poles as much as 5000 m on either side of this pass were drawn toward it and eventually passed through it. The current speed in the pass has been conservatively estimated at between 250 and 500 cm/sec.

The exchange budgets--The following tables summarize the quantitative results of the circulation studies, and are based entirely upon field observations. Despite the abundance of data for the water motions in the lagoon derived from current meter stations, current pole runs, dye drift experiments and bombing runs, and secondary evidence of geological and biological sorts, there are a number of important parameters which have been evaluated by means of an educated guess. These parameters are chiefly those needed to convert velocity data into transport data and involve estimates of the average depth of water over different reef sections, correction for the sinusoidal rate of flow of tidal currents, a correction for the observed maximum current to average current through the passes [SVERDRUP and others, 1942, p. 568], and an assumed steady state during the winter months. These assumptions are evaluated as follows: Average depth of water over the reefs (winter), 100 cm; correction for flow in passes, $V_{aver} = 0.75\ V_{max}$; and correction for sinusoidal tidal flow, $2/\pi$. A further distinction in tabulating the data is made for channels and passes. Channels are broad shallow openings in the reef for which V_{max} and V_{aver} are substantially the same. Passes are narrow V-shaped openings in which bottom and side fraction have important effects upon the measured maximum and average rates of flow. For this reason distinctions are made between passes and channels, and where composite features exist as in the case of Rukoji Channel which has a pass-like notch in its sill, the flows through the pass and channel portions have been separated.

Tables 2, 3, and 4 present data used in computing the volume of water involved in a tidal cycle during the trade-wind season, and show that the volume is approximately 1,060,000 m^3. The total volume of Bikini lagoon is approximately 28,000,000 m^3. Thus 3.8 per cent of the lagoon's volume is transported into and out of the lagoon per tidal cycle. Using this rate it requires about 13 days for the lagoon to exchange its own volume with the sea. This procedure tacitly assumes that every particle of incoming water is retained in the lagoon and every particle of exhausted water is lagoon water. This is inexact to the extent that the passes exhaust on the ebb tide about 70 per cent of the ocean water introduced on the previous flood. Thus the rate of exchange is reduced by an amount which is proportional to the ratio between the rate of exchange through the passes and the "rectified flow" over the reefs. This yields a correction factor of about 3.0, making a more reliable estimated rate of exchange with the open ocean one lagoon volume in 39 days. This value is valid only during the trade-wind season when a steady state can be assumed. Throughout the summer season no prolonged steady state exists, but it was found that the flow through the passes is reduced 50 per cent and that over the reefs nearly 80 per cent. The change in average wind direction from easterly to southerly occasionally forces water out of the lagoon over the northern reefs and makes Enyu Channel an important source of incoming water. It is estimated that the summer average exchange rate is approximately half of the winter rate.

The rate of overturning of the lagoon's primary circulation is calculated to be once in 150 hr for the winter season and once in approximately 300 hr for the summer season.

Table 2--Calculated flow into and out of Bikini Lagoon in the trade-wind season

Reefs	Length	Depth	Velocity				Volume			
			Tide stage				Tide stage			
			High	Ebb	Low	Flood	High	Ebb	Low	Flood
	km	m	cm/sec	cm/sec	cm/sec	cm/sec	m^3/sec	m^3/sec	m^3/sec	m^3/sec
Boby-Namu	0.5	Varies	20	10	10	25	130	40	20	100
Namu-Yuro	8.4	with	40	40	30	45	4350	2700	750	3020
Amen-Bikini	9.8	stage	40	50	25	40	5100	3900	740	3140
Bikini-Enyu	5.4	of	00	40	20	30	2100	1730	320	1300
Boby-West	8.5	tide	- 0	- 15	0	20	0	- 1020	0	1360
West-Boro	6.3		- 5	- 5	5	5	- 410	- 250	90	250
						Sums	11,270	7100	1920	9170
Channels										
Rukoji[a]	3.5	8.7	- 5	- 15	- 5	45	- 1500	- 4500	- 1500	13,700
Enyu	15.7	12.2	-2.5	- 3.0	- 2.5	- 2.0	- 4800	- 5800	- 4800	- 3800
						Sums	- 6300	-10,300	- 6300	- 9900
Passes										
All SW	2.0	29.4	- 10	-100	-15	50	- 5900	-59,000	- 8900	29,400
Rukoji[a]	0.6	36.6	- 5	- 25	- 5	50	- 1100	- 5500	- 1100	11,000
Eniirikku	0.4	55.0	- 5	- 25	- 5	35	- 1100	- 5500	- 1100	7700
						Sums	- 8100	-70,000	11,100	48,100
					Corrected sums for passes		- 6100	-33,400	- 8300	22,900

Positive values denote inflow; negative values, outflow.

[a]Rukoji, a "composite channel," is subdivided into its component parts.

Table 3--Net transport of water at Bikini in trade-wind season per tidal cycle

Tide stage	Duration per cycle	Flow			
		Over reefs	Through channels	Through passes	Total
	hr	m^3	m^3	m^3	m^3
High	0.5	21,000 - 1,000	- 12,000	- 11,000	- 3000
Ebb	5.8	175,000 - 28,000	-215,000	-697,000	-765,000
Low	0.5	3000	- 12,000	- 15,000	- 24,000
Flood	5.2	172,000	256,000 - 71,000	429,000	786,000

Net inflow, 786,000 m^3/day; net outflow, 792,000 m^3/day
Positive values denote inflow; negative values, outflow

Table 4--Total transport of water at Bikini in trade-wind season per tidal cycle

Flow over or through	Inflow	Outflow
	m^3	m^3
Reefs	21,000	1000
	175,000	28,000
	3000	
	172,000	
Channels	256,000	12,000
		215,000
		12,000
		71,000
Passes	429,000	11,000
		697,000
		15,000
Sums	1,056,000	1,062,000

Table 5--Volumes of water transported at Rongelap per tidal cycle

Through	Flood	Ebb
	m^3	m^3
Northeast Pass	94,000	- 60,000
Gogan Pass	20,000	- 20,000
Enybarbar Pass	200,000	- 100,000
South Pass	630, 000	- 374,000
Pigen Pass	44,000	- 35,000
Enigan Pass	35,000	- 30,000
Kaeroga Pass	200,000	- 200,000
West Pass	300,000	- 300,000
	923,000	-1,110,000
Northern reefs	180,000	140,000
Western reefs	- 40,000	- 65,000
	140,000	- 75,000
Total exchange	1,063,000	-1,054,000

The exchange budget for Rongelap is based upon more tenuous evidence consisting of a week of summer observations during which a steady state can be said to have existed. The measured contribution of each pass and estimated contribution of each reef section is shown in Table 5.

The total volume of Rongelap lagoon is approximately 47,000,000 m^3. Thus 2.2 per cent of the lagoon's volume is transported into and out of the lagoon during each tidal cycle. The value is remarkably close to that obtained for Bikini. The winter value may be roughly twice as great.

Secondary results--In the course of the circulation observations, large numbers of current poles were used in groups in combination with fluorescein dye which was trailed from the stern of an anchored skiff that marked the origin of the pole fields. Bundles of 30 poles were freed at the same time that the dye was released in the water to observe the dispersion of both indicators in response to horizontal diffusion in the surface layer of the lagoon. On the assumption that the dye was free of windage and represented the true progress of a given parcel of water in the current, it was found that the poles were unreliable. Only those current poles that were completely awash stayed with the edge of the dye. Others which protruded varying amounts drifted ahead of the dye as a result of their windage. Figure 6 gives the curves of the windage error for 16-ft 2 × 2 inch poles having various lengths exposed to a variety of wind forces. From these curves it appears that a standard current pole, which has 12 inches of its 15 ft of length exposed in air [HAIGHT, 1938, p. 17], is capable of ten per cent error in a 20-knot wind. The addition of pennants, targets, and other aids to visibility increases the possibility of error many-fold.

The dye trails between the skiff and the pole fields frequently took on a sinusoidal shape much exaggerated in Figure 7. The period of the dye wave in Bikini Lagoon was 1500 sec, too long to be

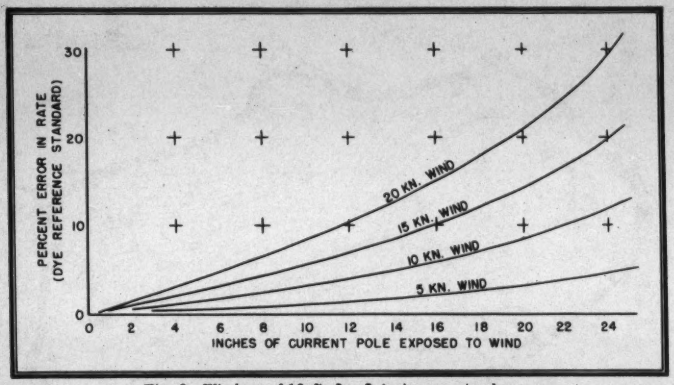

Fig. 6--Windage of 16-ft, 2 × 2-inch current poles

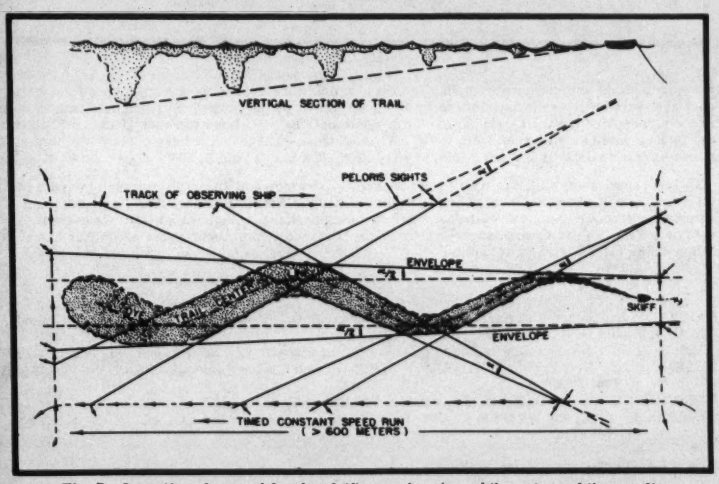

Fig. 7--Operation plan used for dye drift experiments and the nature of the results

accounted for by the yawing of the skiff on her anchor rode. The wave length of the trail was usually of the order of 300 m and the amplitude 25 m. The angles α marked on the figure to represent the divergence of the dye in the trail, and also the divergence of the trail envelope, were found to be equal and to have values ranging from 08° to 14°. This identity indicates that the center line of the trail had constant amplitude and period and that the divergence of the trail and of its envelope both result from eddy diffusion. The angles of divergence were independent of the speed of the surface current but closely related to the amount of shear in the upper 15 ft of the surface layer. The shear was observed qualitatively by means of weighted dye-packs which left a vertical dye trail in the water. The vertical section of the dye trail was seen to have downward

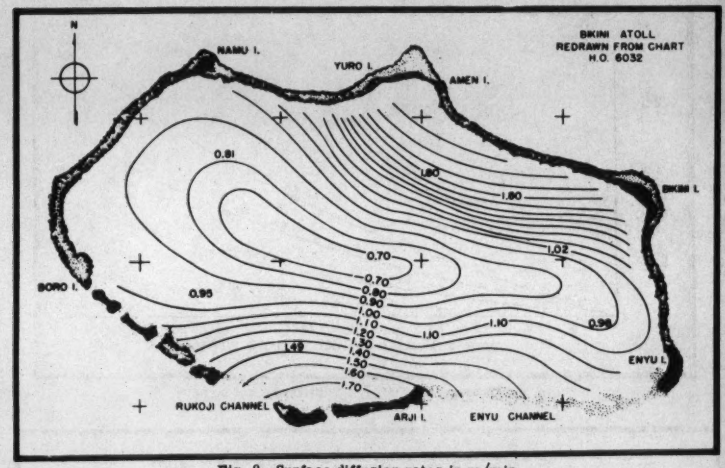

Fig. 8--Surface diffusion rates in m/min

developments at approximately regular intervals which were deeper as one approached the distal part of the trail. It was impossible to fix the positions of the downward developments with respect to the sinuosity of the trail because the latter could only be seen from the ends of the trail while the former could only be seen from the sides. Analogous patterns have been observed in airborne smoke trails over the sea surface [WOODCOCOCK and WYMAN, 1947, plates 2 and 4].

Ten experiments with dye trails and poles were performed at Bikini to measure the rate of lateral diffusion on the surface. These data are plotted in Figure 8 and lines of equal diffusion rate drawn through them, calculated as the rate of expansion in m/min of an equivalent dyed spot of water. The vales are larger wherever the horizontal component of the secondary circulation of the lagoon is most active.

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OCEAN CIRCULATION IN MARSHALL ISLANDS AREA

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(Contribution No. 420, Woods Hole Oceanographic Institution)

Abstract--Salinity and temperature observations were made from Naval vessels during Operation Crossroads for the purpose of determining the probable drift of radioactive material around Bikini. These observations have been subjected to water-mass analysis, and dynamic computations have been carried out. Results are compared with Japanese and other data from the region. Approximate temperature-salinity correlations at different latitudes in the transition from the deeper Pacific Equatorial Water to shallower western North Pacific Central Water are shown.

Introduction--As a part of Operation Crossroads, an oceanographic survey was conducted to provide information on the probable drift of radiologically contaminated water away from Bikini Atoll. This survey was made during the months of March to August 1946. A total of 240 temperature-salinity stations was occupied in the Marshall Islands area between the parallels of 3°S and 20°N and the meridians of 162°E and 172°E. Although the larger number of these stations was within a 100-mile radius of Bikini, four sections were extended south across the Equator and two north to latitude 20°N. The coverage is most representative of the summer months of July and August. At the time the expedition was organized the only available deep-water observations were those from three stations in the northern part of the area occupied by the Carnegie in May 1929 [FLEMING, ENNIS, SVERDRUP, SEATON, and HENDRIX, 1945, pp. 226-227]. Figure 1 shows the location of the Carnegie and Crossroads stations. Data from approximately 400 Japanese stations occupied in this general area during the period 1935 to 1942 have since become available. These data have been superficially examined and compared with the Crossroads observations, but time has not permitted a detailed analysis.

Crossroads observations were made with common oceanographic techniques, using Nansen bottles and protected and unprotected reversing thermometers. Lowerings of 900-ft bathythermographs were also made at each station to supplement temperatures obtained from the reversing thermometers. The observations were made from five naval vessels, four being used simultaneously during late June and July, and two early in August.

Because of the recent War, many of the thermometers used lacked calibration certificates and those having certificates had not been checked for many years. The thermometers are now being calibrated. Preliminary determinations indicate an average change in the ice point of 33 thermometers of +0.03°C, with a range from 0.00 to + 0.06°. Although it is not expected that the general picture of circulation in the area will change when corrected values are available, detailed topography of particular localities may vary, and the depth and temperature observations reported herein are to be regarded as provisional. Unfortunately, not all the salinity samples were titrated, and for the purposes of this discussion the missing salinities have been estimated from temperatures using the temperature-salinity correlation for the appropriate latitude.

General--The predominating currents in the vicinity of the Marshall Islands are the westerly-directed North Equatorial Current north of latitude 6° or 8°N and occupying the area of the northeast trade winds, the easterly-directed Equatorial Counter Current in the doldrum belt between the North Equatorial Current and the vicinity of the Equator, and the South Equatorial Current setting west, south of the Equator. Boundaries of these currents are considered as shifting northward with the Sun in northern summer and southward in the winter. Water masses of primary interest in this region are the western North Pacific Central Water occupying the area north of the Equatorial Counter Current, and the Pacific Equatorial Water in the area of the Counter Current (see Fig. 2). On the south, the area borders on western South Pacific Central Water. A subsurface intrusion of Intermediate Water from the zone of Subarctic Convergence may be found in the northern part of the area.

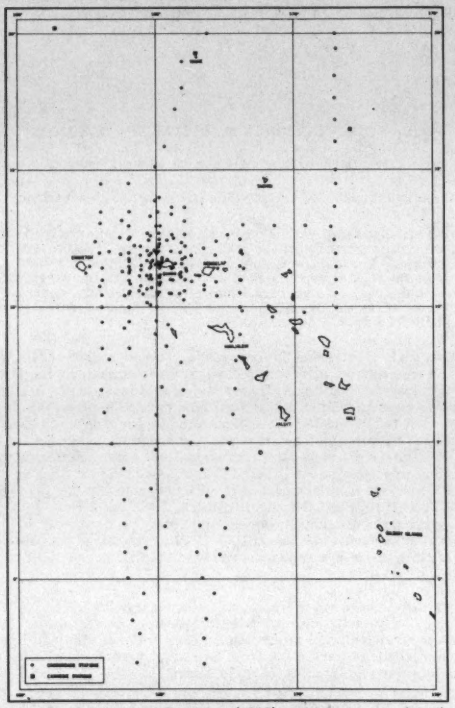

Fig. 1--Positions of Carnegie (1929) and Crossroads (1946) oceanographic stations

Temperature--In general, the vertical temperature distribution consists of a virtually isothermal layer from the surface to 75 m, a strong main thermocline from 150 to 300 m, and a deep, weak gradient below 300 m toward the bottom. The temperature ranges from 27° to 29°C at the surface (temperatures slightly less than 26°C at the surface have been reported for the northern part of the area during earlier months of the year) to about 10°C at 300 m and to about 3°C at 1500 m.

The north-south distribution of temperature is illustrated in Figure 3, a profile of temperature along the meridian of 166° E (longitude of Bikini). The shallower isotherms, which are nearer the surface in the center of the area, latitude 7°N, corresponding to a region of low salinity, dip toward the north in the region of the Northern Equatorial Current and then rise from latitude 17°N in what appears to be transport in an easterly direction. This inclination of the isotherms is also apparent in the Japanese data collected in the region.

Commencing at latitude 7°N, the shallow isotherms dip slightly toward the south, the maximum slope occuring in the region of the Equatorial Counter Current. The sharp dip in the 10°C isotherm is evidence of the intrusion of western South Pacific Water.

Salinity--The salinity distribution is depicted by Figure 4, a profile of the same stations as shown in Figure 3. The center of the area between 3°N and 11°N is occupied by water of relatively

low salinity; there is but slight vertical structure between 7°N and 11°N. These are latitudes of high precipitation, and in addition, water of low salinity is being brought in from the west by the Equatorial Counter Current. To the northward, the surface salinities rise in the region of higher evaporation. There is evidence as far south as 11°N of the intrusion of North Pacific Central Water under the less saline surface water. This is borne out by the appearance of the 35 0/00 isohaline.

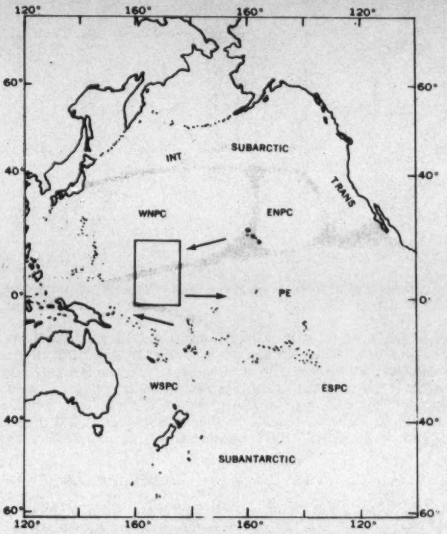

Fig. 2--Pacific Ocean showing water masses [after SVERDRUP, JOHNSON, and FLEMING, 1942] and region in which Crossroads oceanographic stations were occupied; arrows show the set of currents; abbreviations; INT, Intermediate Water; TRANS, Transition Region; WNPC, western North Pacific Central; ENPC, eastern North Pacific Central; PE, Pacific Equatorial; WSPC, western South Pacific Central; PE, Pacific Equatorial; WSPC; western South Pacific Central; ESPC, eastern South Pacific Central

An intrusion of western South Pacific Central Water with relatively high salinity crosses the Equator from the south under the less saline Equatorial Counter Current, as shown by the 34.8 0/00 isohaline and the 10°C isotherm. The region between latitudes 4°N and 11°N appears at shallow depths to be that of vertical mixing of the fresher surface water as described by SVERDRUP, JOHNSON, and FLEMING, 1942, p. 711] and of lateral mixing at greater depths of the more saline waters from the north and south. The sigma-t surface of 26.0 is shown extending from water of 35.4 0/00 on the south to 34.4 0/00 water on the north. The underlying water is Pacific Equatorial Water, which is present near the surface (300 m) to latitude 12°N and deepens to 1100 m at 20°N. Between the Pacific Equatorial Water at depth and the western North Pacific Central Water near the surface, there is an intrusion of Intermediate Water of the North Pacific. This is shown by the 34.2 0/00 isohaline at 600 to 700 m.

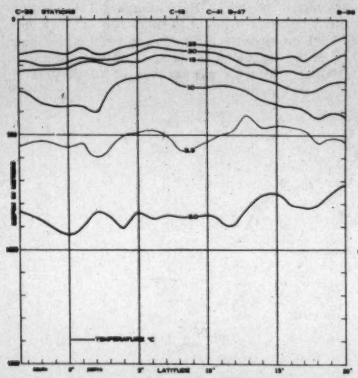

Fig. 3--Vertical temperature distribution along the meridian of Bikini (166°E)

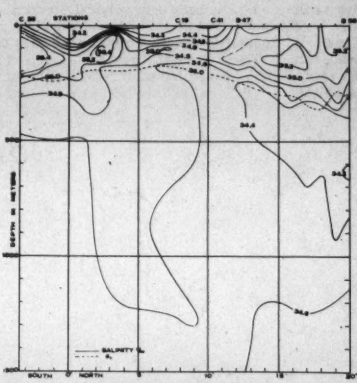

Fig. 4--Vertical salinity distribution along the meridian of Bikini (166°E)

Figure 5 shows the temperature-salinity relationships of the western North Pacific Central Water and the Pacific Equatorial Water as defined by SVERDRUP, JOHNSON, and FLEMING, 1942, pp. 706-745]. The solid lines in the left side of the diagram show approximately the appearance of the temperature-salinity correlations at different latitudes in the transition from the deeper Pacific Equatorial Water to the shallower western North Pacific Water. At latitude 20°N the water is all North Pacific Water; at 15°N the transition zone commences at 700 m (see the insert to Fig. 5) and ends at 400 m; while at 10°N the transition zone lies above 200 m and is less than 50 m thick.

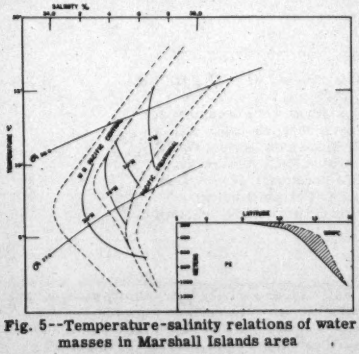

Fig. 5--Temperature-salinity relations of water masses in Marshall Islands area

Dynamic topography--The dynamic topography of the area has been computed from the temperature-salinity-depth measurements. Figure 6 shows anomalies of dynamic heights of the surface expressed in units of dynamic centimeters and referred to the 1000-decibar level. The contours indicate a generally westward set of the current between the latitudes of 8°N and 17°N. The drift of this North Equatorial Current averages approximately one-third knot over most of this latitude range, but is variable with a maximum of nine-tenths knot west of Bikini Atoll. The presence of eddies northwest and northeast of Bikini is indicated. Japanese data also show a probable eddy to the northeast, but stations were too widely spaced to confirm the leeward eddy. Drift-pole studies conducted in April and May showed a westerly set south of Bikini Atoll with drift rates varying from 0.3 to 0.4 knot at a distance of ten mi south of the periphery of the atoll to one knot within a distance of two mi of the islands. Although the general drift of the poles was westerly, they drifted northwest south of the eastern end of the atoll, changed to west as they approached the atoll, and shifted southwest near the western end of the atoll. This drift roughly parallels the 190 dynamic cm contour shown for that vicinity in Figure 6 and indicates that the detailed topography may be quite complex. The two island chains terminating near the latitude of Bikini no doubt contribute to the complexity of the local surface topography of the area. The apparent reversal of current between latitudes 6° N and 9° N may be a partial result of the damming of the flow by the closely grouped atolls to the east.

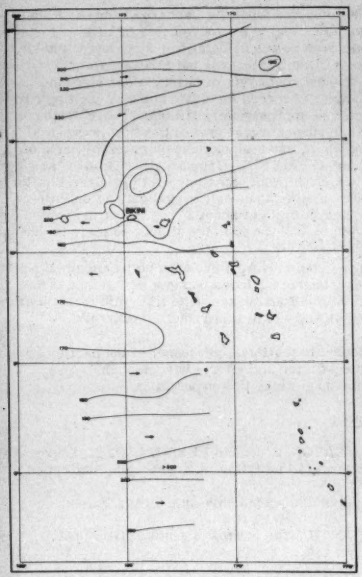

Fig. 6--Dynamic topography of the sea surface relative to the 1000-decibar surface, Marshall Islands area, in units of dynamic centimeters

North of 17°N the contours show an easterly setting current of approximately 0.8 knot, but measurements at this latitude are too few to exclude the possibility of an eddy. South of 7°N the Equatorial Counter Current sets eastward. The velocities obtained from dynamic calculations were as high as two knots, but the use of the Bjerknes method at these low latitudes is open to question.

Related temperature measurements were made and salinity samples taken over a 20-hr period at one location near Bikini (lat. 11°28′N, long. 165°15′E). The anomalies of dynamic heights of the surface referred to the 300 decibar level for nine series of measurements varied from 118 to 123 dynamic cm, with an average deviation of 1.3 dynamic cm and a probable variation of each determination from the mean of 1.6 dynamic cm. It is believed that this variation is largely occasioned by internal waves. Using these observed values as a basis and assuming a station spacing of one degree of latitude (60 mi), variations at one station alone would cause computed currents to fluctuate by the amounts shown in Table 1 at different latitudes.

If one station were occupied at the crest of the wave and the other at the trough the fluctuations would be double the above values. The existence of internal waves is confirmed by bathythermograph studies which are the subject of the paper by LA FOND [publication pending].

The same general pattern of dynamic topography prevails at 300 m as at the surface, but calculated velocities are less than one-third those at the upper level. Figure 7 shows smoothed

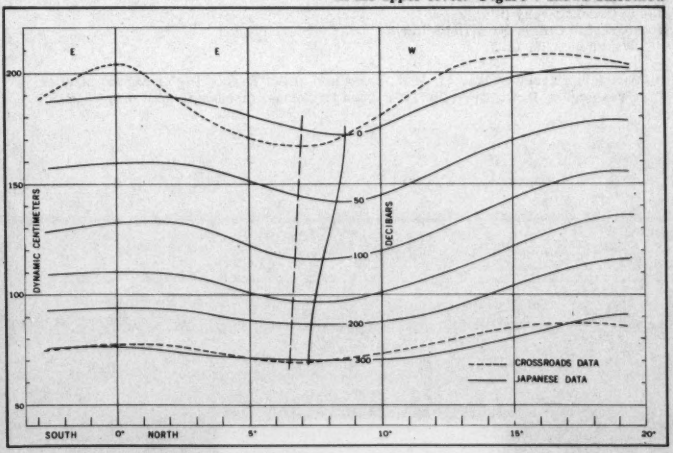

Fig. 7--Smoothed profile of isobaric surfaces relative to the 1000-decibar surface, Marshall Islands area

profile isobaric surfaces for north-south sections as obtained from the Crossroads (broken line) and Japanese (solid line) data. The averaging of dynamic heights for increments of latitude for this area obscures details of topography and effects of internal waves but stresses the persistent features. Both sets of observations show the boundary between the east- and west-setting currents at approximately latitude 7° or 8°N, the pronounced current toward the west between 8° and 15°N, and a slackening or reversal north of about 15° to 17°N. Crossroads data show the Counter Current extending south past the Equator, whereas the Japanese data indicate no definite direction south of about 2° or 3°N. Currents south of 10° are confined almost entirely to the upper 300 m.

Table 1--Fluctuation of the current

Latitude	Fluctuation in calculated current
°	knot
2	0.5
3	0.4
4	0.3
5-7	0.2
8-20	0.1

The profile of the sea surface based on Crossroads data shows a pronounced maximum at the Equator, in agreement with theory which requires of isobaric surfaces maxima or minima at that latitude. The other surfaces depicted in the vicinity of the Equator are quite flat, with maxima or minima too poorly defined to be of much significance in support or contradiction of theory.

Acknowledgments--The authors are deeply indebted to the Naval personnel of the participating vessels and to the many civilian observers whose cooperation and efforts have contributed so much to the collection and analysis of the information upon which this paper is based.

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ACTIVITY OF PARÍCUTIN VOLCANO FROM APRIL 1 TO JULY 31, 1948

Ray E. Wilcox and Celedonio Gutiérrez

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A record of the activity of Parícutin Volcano, Michoacán, from April 1 to July 31, 1948, is shown diagrammatically in Figure 1, and the areas covered by lava during this period are represented on the map in Figure 2. An explanatory discussion of the diagram of eruptive characteristics and a description of the lettered noise types appear in a previous report [WILCOX, 1947]. Data for variations in tide-producing force were furnished by the United States Coast and Geodetic Survey.

Activity of the cone--The pyroclastic activity of the main cone during this period was generally weak (see Fig. 1), the only prolonged strong eruptions of pyroclastics occurring June 11-13, 29-30, and July 22-29. Vapors continued to be given off strongly, however, during much of the time when the pyroclastic eruptions were weak.

Occasionally there were periods characterized by puff-like eruptions of ash and bombs, too brief to be represented on the scale of Figure 1; these occurred notably April 7, May 17-21, June 9, and July 1-2, 6-8, and 30. A single explosion of great intensity on May 25 threw bombs to a distance of more than one km in the northwestern quadrant from the crater vent. These puffs were similar to the frequent pyroclastic explosions of December 1947 and January 1948 [WILCOX, 1948, p. 355], but were for the most part less intense. The normal sequence leading up to an explosion of this type was a gradual decrease in the quantity of ash for a period of five to 15 min, often followed by an apparent complete cessation of eruptions for a minute or two, and then a sudden grand burst of ash and bombs that might continue for five min or more before moderating.

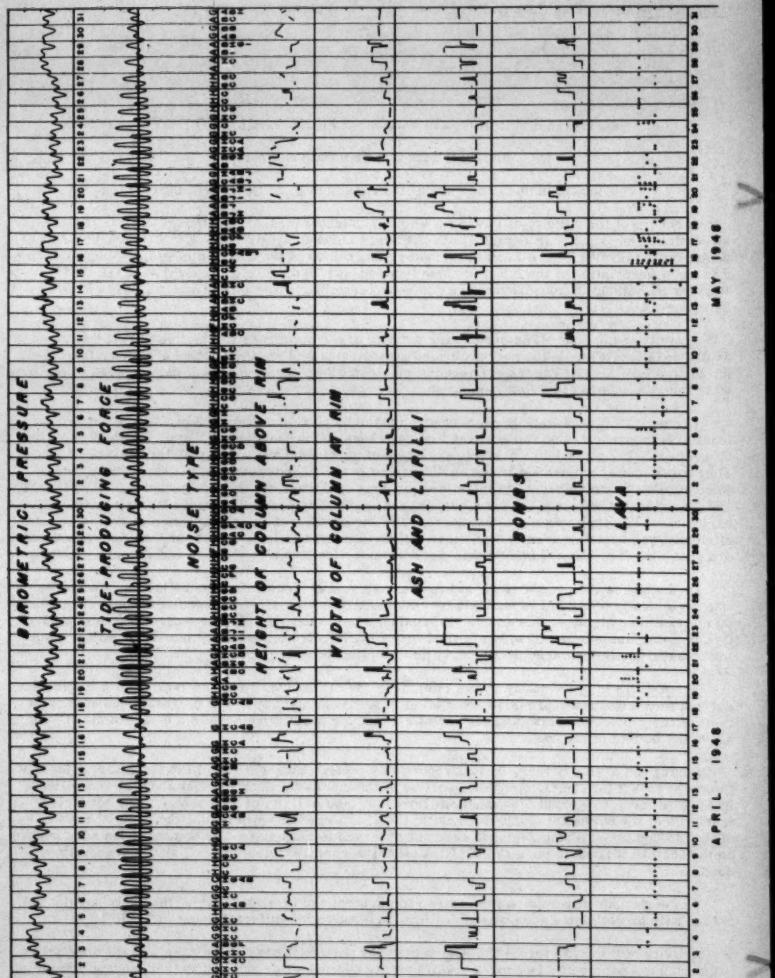
On ascending the cone May 17, a single crater vent clogged with viscous lava was seen, which was periodically blown out in part and torn into shreds by the strong surges of vapors. The bombs so ejected were highly vesicular and, on landing, some were still plastic enough to flatten. This type of bomb, the surface of which is light brown, differs from the black, usually more dense and less plastic bombs that accompany heavy ash eruptions.

Form of the cone--On May 17 the interior of the crater was a shallow bowl with a single vent set in a funnel-shaped depression about 30 m in greatest diameter. The northeast and southwest rims of the crater were low, and the northwest and southeast rims rose to a height of about 70 m above the bottom of the bowl.

During the period covered by this report only minor changes occurred in the external form of the cone, except for the slumping of a portion of the southwest flank brought about by the collapse in April of the area around the Puertecito lava vent (see Activity of lava vents). The bordering fractures of the northeast slump segment of the cone were reopened from time to time, but those of the old southwest slump segment were not observed to reappear. The bomb-eroded rills present on the northwest flank in January [WILCOX, 1948] were still visible in May, although greatly subdued.

The elevations of points on the crater rim, determined by alidade from Cuzeño triangulation station with an estimated accuracy of $\pm$ 1.5 m, are shown for different dates in Table 1.

Activity of the lava vents--The lava vent at the northeast base of the cone was the only active one during the period of this report, and its nearly continuous production varied generally from moderate to great, as shown in Figure 1. With repeated overflowing of the vent and the outlet channels, the vent mound rose to form a separate conelet at the base of the main cone. The outlet channel to the north, which had persisted since March 10, clogged June 4-5 during a temporary lull in the flow of lava, and thereafter all the lava cascaded down the northeast flank of the vent mound in a channel that had been carrying some lava since May 25. On July 10 the lava abandoned this latter channel and flowed down the northwest face of the mound. A fresh cascade down the north face began July 28 while the northwest cascade continued.


BAROMETRIC PRESSURE
inches Mercury
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HEIGHT OF COLUMN ABOVE RIM
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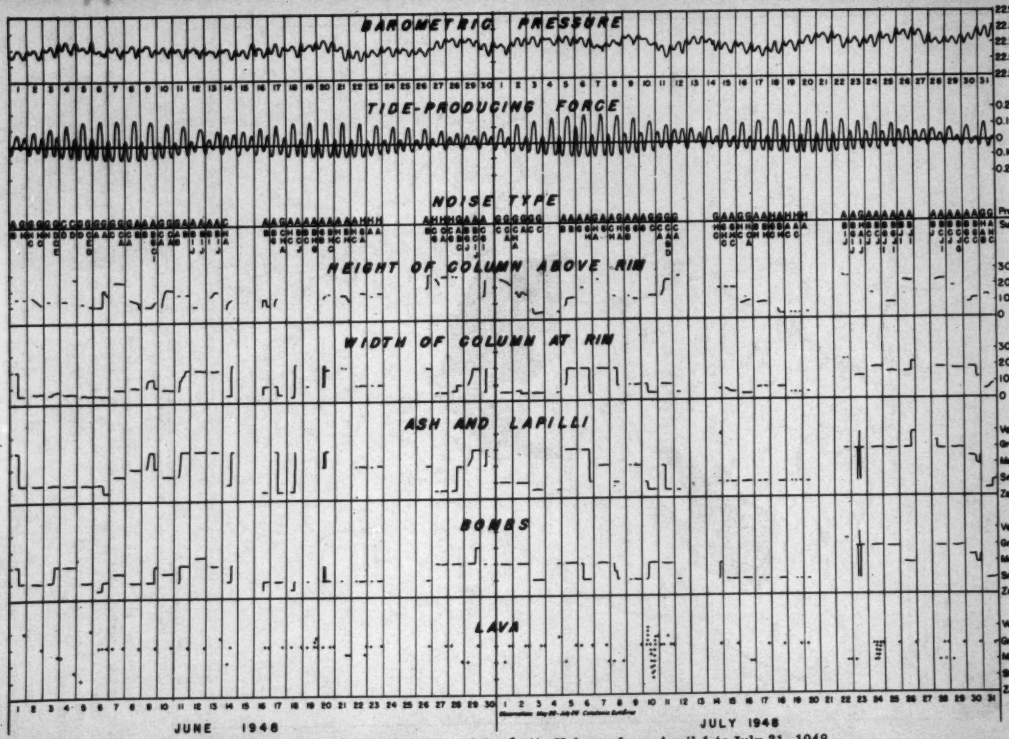

Fig. 1--Eruptive characteristics of Parícutin Volcano from April 1 to July 31, 1948

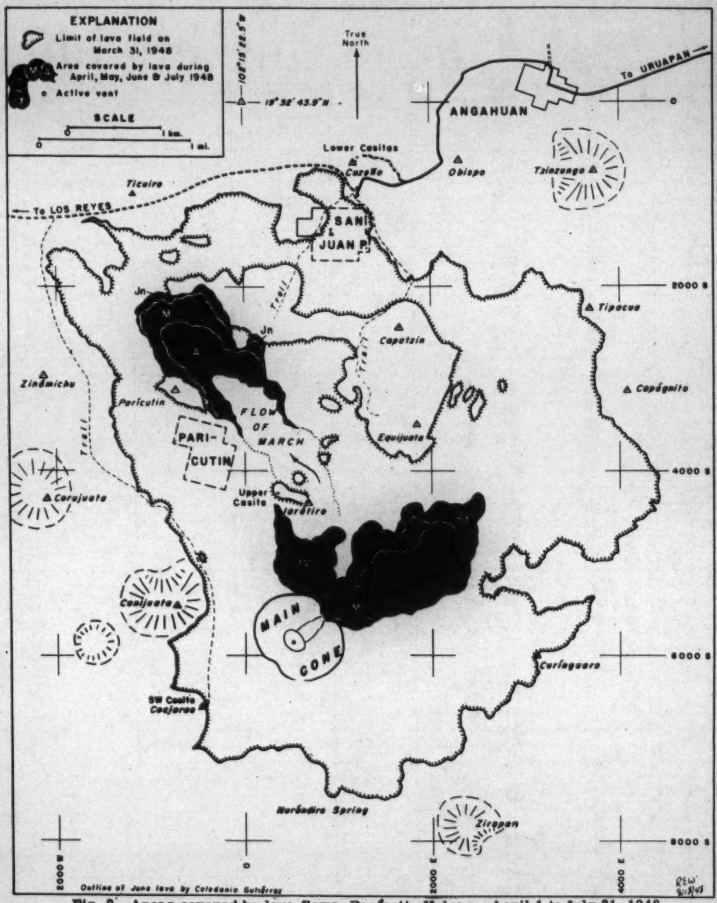

Fig. 2--Areas covered by lava flows, Parícutin Volcano, April 1 to July 31, 1948

Two strong explosions at the lava vent occurred May 16, tearing apart huge masses of viscous lava and scattering them for distances up to 60 m from the vent. These explosions, separated by an interval of three hours, were of an intensity much greater than any witnessed previously by the writers at the lava vent and took place during a period when the flow of lava had become abnormally sluggish.

During April 1 to July 31 no lava was observed to come from the vents at the southwest base of the cone. A large collapse of the Puertecito vent, at the immediate southwest base of the cone, occurred sometime before April 22. On May 17 the roughly circular border of this collapsed area

Table 1--Elevations above sea level of points on the crater rim

Date	West Peak	Lowest point in NE rim	East Peak
1948	m	m	m
March 31	2773.2	2754.9	2775.0
April 30	2772.4	2741.9	2773.4
May 28	2772.4	2741.1	2771.9
June 30	.....	Not determined	.....
July 31	2770.9	2739.5	2772.6

was about 70 m in diameter, and the bottom was about 40 m below the level of the western edge. The walls, where not composed of rubble and talus, showed massive lava. The northeast edge of the collapse had encroached on the cone proper and had drawn down a portion of the cone material. No fumarolic activity of appreciable magnitude was observed within the depression, although hot vapors issued from a fractured zone that extended along the base of the cone for a distance of about 40 m northwest from the collapse.

The medial portion of the Ahuan lava vent, 100 m south-southeast of the Puertecito vent, likewise collapsed to form a depression about 30 m long. The Mesa de los Hornitos lava vent did not undergo any recognizable change in form during this period, although it continued to give off hot vapors.

Activity of the lava flows--The areas invaded by new lava are shown in solid black in Figure 2. The flow of February and March continued to advance northwestward but in decreasing monthly increments until it ceased entirely the latter part of June. This flow, with a total length of about 4100 m, is the longest flow in two years. A lobe started northeast from the vent May 25, and by the end of July, when movement had virtually ceased, its length was about two km. With the change of the lava cascade to the northwest flank of the vent mound July 10, a new lobe started northward over the February flow, and its active front had reached almost to the western base of Jarátiro Hill by the end of July. A narrow lobe (not differentiated on Figure 2) fed by the newly opened north outlet channel started north-northeast July 28 and had advanced about 400 m by July 31.

The lava movement was sluggish, and as usual, the flows developed mantles of coarse red-brown rubble. On several occasions sharp gas discharges from the moving lava near the source threw fragments as much as 15 m into the air. Sharp pistol-like dischares frequently were heard from the lower reaches of the flow as a result of spalling and flaking of cooling blocks.

Weather data--The results of daily weather observations at Cuzeño station are summarized in Table 2. The average upper-wind direction expresses the direction of the wind carrying the major portion of the erupted ash and vapors. Barometric pressures appear in Figure 1.

Table 2--Monthly summaries of daily weather observations, Cuzeño station, Parícutin Volcano

Month	Temperature		Rainfall		Ashfall		Minimum humidity	Average upper wind direction
	Max.	Min.	Total	Max.	Total	Max.		
1948	°C	°C	mm	mm	mm	mm	pct	
April	30.8	5.8	53.0	18.2	tr	tr	20	NE
May	29.2	7.5	99.3	24.7	0.2	0.2	..	NNW
June	25.0	10.0	232.1	36.0	1.2	0.8	..	ENE
July	22.8	9.8	359.8	73.5	1.0	0.5	56	E

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U. S. Geological Survey,
Washington 25, D. C.

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VEDERNIKOV'S CRITERION FOR ULTRA-RAPID FLOW

Ralph W. Powell

Abstract--A criterion is given for the stability of steady uniform flow in open channels. When this number exceeds one, the flow is ultra-rapid, roll waves form, and the flow cannot be steady. This criterion is compared with several which have been proposed, and is judged to be more comprehensive and exact.

An empirical formula for Chezy's "C" in ultra-rapid flow is derived from data already published by the author.

Introduction--In two very interesting papers published in Russian but available in English, VEDERNIKOV [1945 and 1946] has developed a criterion for the stability of steady uniform flow. He says that when the criterion is less than one, waves tend to dampen out, but that when it is equal to or more than one, they amplify so that steady flow is impossible and we have what he calls ultra-rapid flow. Others have used the expressions roll waves or slug flow.

This criterion, which I am calling the Vedernikov number, may be written as

$$\underline{V} = (1 + \beta)MV/p(u - V) \quad \ldots\ldots (1)$$

where V is the mean velocity across any section, u is the velocity of the wave, and β and p are exponents in the resistance equation

$$S = k V^p/R^{(1 + B)} \quad \ldots\ldots (2)$$

and M measures the effect of the shape of the cross section and is defined by

$$M = 1 - RdP/dA \quad \ldots\ldots (3)$$

where S = slope of energy gradient, R = hydraulic radius, P = wetted perimenter, and A = area of cross section. We also have the well known relationship

$$u - V = \sqrt{gA/\alpha B} \quad \ldots\ldots (4)$$

where B = top width, and α is the coefficient which corrects for nonuniformity in the velocity distribution.

Development--In rough channels it is now known that for tranquil flow Chezy's C is constant for any one relative roughness, and in (2), p = 2 and $\beta = 0$. In smooth channel flow on the other hand, C is a function of the Reynolds number, which requires that $p + \beta = 2$, as can be seen by writing $S = k V^p/R^{(1 + \beta)} = V^2/C^2R$ and $(C^2k = V^{(2 - b)}R^{\beta})$. Since in Reynolds number $\underline{R} = 4VR/\nu$, the velocity and the hydraulic radius have the same exponent, this requires that $2 - p = \beta$.

In his papers, Vedernikov has much of the time taken p = 2, without at the same time taking $\beta = 0$. In fact Manning's formula makes p = 2 and $\beta = 1/3$, but it is beginning to be realized that Manning's formula is a not-too-successful attempt to make the same law cover both smooth and rough channel flow. In what follows we will take $p + \beta = 2$, which leads to another form of the criterion

$$\underline{V} = (1 + \beta)MV/(2 - \beta)\sqrt{gA/\alpha B} \quad \ldots\ldots (5)$$

If we define the Froude number $\underline{F}$ as the ratio of the mean velocity of flow to the velocity of a gravity wave in still water, we have from (4)

$$\underline{F} = V/\sqrt{gA/\alpha B} \quad \ldots\ldots (6)$$

and substituting in (5) we have

$$\underline{V} = (1 + \beta)M\underline{F}/(2 - \beta) \quad \ldots\ldots (7)$$

and the critical value of $\underline{F}$ for which $\underline{V} = 1$ is

$$\underline{F}_c = (2 - \beta)/(1 + \beta)M \quad \ldots\ldots (8)$$

Combining (7) and (8), we have

$$\underline{V} = \underline{F}/\underline{F}_c \quad \ldots\ldots (9)$$

For a rectangular channel, $A = By$, $P = B + 2y$, and $R = By/(B + 2y)$. Also $dP/dA = (dP/dv)/(dA/dy) = 2/B$, so that from (3), $M = 1 - 2y/(B + 2y) = B/(B + 2y) = 1/(1 + 2y/B)$. Therefore, from (8), for a rectangular channel

$$\underline{F}_c = [(2 - \beta)/(1 + \beta)]\,(1 + 2y/B) \quad \ldots\ldots (10)$$

Comparison with other criteria--In a very narrow channel, $\underline{F}_c$ would be very large and ultra-rapid flow would hardly ever occur. On the other hand, in a very wide channel the $(1 + 2y/B)$ in (10) approaches one, and $\underline{F}_c = (2 - \beta)/(1 + \beta)$. For rough channel flow, $\beta = 0$ and $\underline{F}_c = 2$. This is the value given by JEFFREYS [1925] and by THOMAS [1939].

For smooth channel flow with $\beta = 0.20$, the wide channel gives a critical Froude number of $1.8/1.2 = 1.5$, which is the result obtained by KEULEGAN and PATTERSON [1940] by quite different reasoning.

Lea's formula for smooth channels gives $\beta = 0.25$, and $\underline{F}_c = 1.40$ as given by ROBERTSON and ROUSE [1941].

The advantage of Vedernikov's criterion is that it is much more general than those heretofore proposed, applying to channels of any shape, and to both smooth and rough channel flow, and that it shows how to correct for the effect of non-uniform velocity distribution.

One interesting result is that for laminar flow in very wide channels (sheet flow), $\beta = 1$, $M = 1$, and $\underline{F}_c = 0.50$. This seems to indicate that with increasing velocity, tranquil flow will change to ultra-rapid directly, without passing through the rapid stage. This result seems to be implied in the article by ROBERTSON and ROUSE [1941].

The question as to what value of β should be used in any given case may be answered as follows. For non-turbulent flow, $\beta = 1$ and $\underline{V} = 2M\underline{F}$. For turbulent rough-channel flow, $\beta = 0$ and $\underline{V} = M\underline{F}/2$. For turbulent smooth-channel flow, (2) may be combined with Chezy's formula to give $\underline{C}^2 = (VR)^{\beta}/k = \underline{R}^{\beta}\gamma^{\beta}/4^{\beta}k$. Differentiating this and making various substitutions we have

$$\beta = (2\underline{R}/C)(dC/d\underline{R}) \quad \ldots\ldots (11)$$

An as yet unpublished study by the writer indicates that for rapid flow in smooth channels

$$C = 41.2 \log_{10} (\underline{R}/C) + 17.9\,\beta_k \quad \ldots\ldots (12)$$

where β_k is the shape correction used by KEULEGAN [1938, Eq. (53)...].

Regarding β_k as a constant and differentiating (12) gives $(dC/d\underline{R})[1 + 41.2 \log_{10}(e)/C] = 41.2 \log_{10}^{e}/\underline{R}$, which combined with (11) gives

$$\beta = 1/(0.0279\,C + 0.5) \quad \ldots\ldots (13)$$

Values from this formula are plotted in Figure 1. The values of $\underline{R}$ there given are from (12) with two different values of β_k. The upper line is for $\beta_k = 0$, which is the value for infinitely wide channels. The lower line is for $\beta_k = 0.19315$ and $17.9\,\beta_k = 3.46$, which is the maximum value for rectangular channels and occurs when the depth is half the width.

Experimental test--As a test of this criterion, some data obtained by the writer [POWELL, 1946] on flow in a rectangular flume were used. It should perhaps be noted that while by title the study dealt with rough channels, data were at the same time obtained on smooth channels. It was

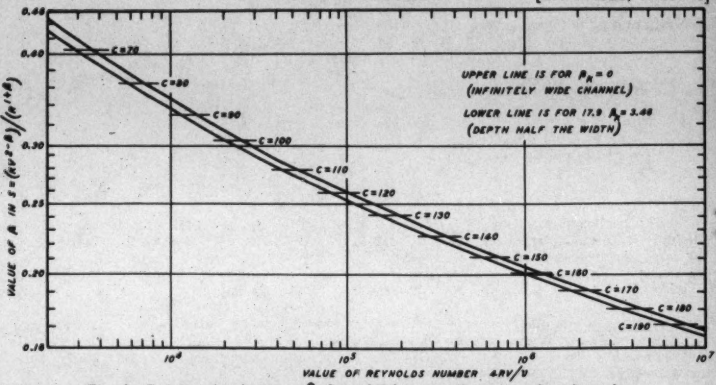

Fig. 1--Relationship between β, C, and R for smooth rectangular channels

found that all the runs in the smooth channel with the steepest slope (those in part (b) of Table 1 of POWELL [1946], gave V more than one, while all runs in the smooth channel with flatter slopes (those in part (a), and all those in the rough channels (parts (c) to (n) inclusive) gave V less than one, thus checking Vedernikov's theory. Incidentally the writer was mistaken in his classification in his earlier paper. The heading of part (a) should have been Tranquil and Shooting (or Rapid) Flow, and the heading of part (b), Ultra-rapid Flow. Runs 46 and 24 were tranquil, and Run 23, shooting, but both followed the same law of resistance. Runs 1, 2, 3, and 8 at the steepest slope were ultra-rapid with waves forming, and the law of resistance changed. Many of the runs in rough channels at the steepest slope, and part of the runs quoted from Bazin in part (n) of the table were also shooting flow with F more than 1.00, but for all of these V was less than 1.00. A few of these with the highest values are included in Table 1 of this article.

The method of computing Table 1 was as follows: For the rough channels, β was taken as zero, and for the smooth channels it was computed from the observed Chezy coefficient by (13). Using these values of β, the critical Froude number, F_c, was computed by (10), the channel width B being 0.682 ft.and the values of the depth y being taken from Table 1 of POWELL [1946]. The Froude number F was computed from (6), which for rectangular channels reduces to $F = V\sqrt{\alpha/gy}$. Values of V and y were taken from Table 1 of POWELL [1946], and g was taken as 32.16 ft/sec^2. Following KEULEGAN [1942], α was defined as the ratio of the mean of the squares of the velocities to the square of the mean velocity. Its actual value was unknown and probably varied from runtto run, but for want of a better value it was taken as 1.02. The resulting values of F are this about one per cent larger than those given by POWELL [1946] where α was omitted from the definition of F. The Vedernikov number, V, was then computed by (9). To avoid computational errors from accumulating, the computations were made on a machine to four figures, although it is realized that the data are not nearly that accurate.

Formula for ultra-rapid flow--It seemed natural to suppose that the law of resistance for ultra-rapid flow would include the Vedernikov number. A statistical study of the data checked this assumption, but showed that the best fit required a term for F as well as one for V. The resulting equation was

$$C = 41.2 \log_{10} (R/C) + 42.3\, F - 21.8\, V - 113.7 \quad \ldots\ldots\ldots\ldots\ldots (14)$$

which by (9) can be put in the form

$$C = 41.2 \log_{10} (R/C) + 42.3\, V (F_c - 0.515) - 113.7 \quad \ldots\ldots\ldots\ldots\ldots (15)$$

It was not thought necessary to retain any c_s term, since the M in the Vedernikov number is supposed to evaluate the effect of shape. By means of a table of values of C + 41.2 $\log_{10}$ C, the values of C by (14) were computed and tabulated in Table 1, and the discrepancies from the observed values listed. The mean discrepancy is 2.15, instead of 2.44 as given by the former formula. The

Table 1--Data for computing Vedernikov Number, and computed value of Chezy's "C" by (14)

Run	Observed C	β	F_c	$F = 0.1781V/\sqrt{y}$	$V = F/F_c$	Computed C	Discrepancy -	Discrepancy +
1- 1	103.4	0.295	1.757	2.725	1.551	100.9	2.5	. .
1- 2	111.3	0.277	1.903	2.805	1.474	110.0	1.3	. .
1- 3	115.6	0.268	1.963	2.842	1.448	113.3	2.3	. .
1- 4	118.7	0.262	2.282	2.643	1.158	117.7	1.0	. .
1- 5	123.5	0.253	2.445	2.634	1.077	121.1	2.4	. .
2- 1	122.1	0.256	1.899	3.311	1.744	124.5	. .	2.4
2- 2	116.1	0.267	1.841	3.081	1.674	115.0	1.1	. .
2- 3	115.6	0.268	1.830	3.040	1.661	113.3	2.3	. .
2- 4	118.3	0.263	1.823	3.108	1.705	114.5	3.8	. .
2- 5	120.1	0.260	1.863	3.154	1.693	117.9	2.2	. .
2- 6	114.5	0.271	1.818	3.021	1.662	112.4	2.1	. .
2- 7	129.1	0.244	2.228	3.060	1.373	129.5	. .	0.4
2- 8	127.4	0.247	2.227	3.044	1.367	129.2	. .	1.8
2- 9	127.1	0.247	2.231	3.047	1.366	129.6	. .	2.5
2-10	132.9	0.238	2.554	2.818	1.103	130.0	2.9	. .
2-11	116.3	0.267	1.889	2.974	1.574	115.0	1.3	. .
2-12	116.2	0.267	1.941	3.038	1.565	119.6	. .	3.4
2-13	116.2	0.267	1.933	3.021	1.563	118.6	. .	2.4
3- 1	110.3	0.280	1.738	2.942	1.693	106.5	3.8	. .
3- 2	112.4	0.275	1.868	2.935	1.571	113.5	. .	1.1
3- 3	111.6	0.277	1.891	2.946	1.558	115.2	. .	3.6
3- 4	116.7	0.266	1.996	2.885	1.445	117.2	. .	0.5
3- 5	118.9	0.262	2.104	2.891	1.374	121.3	. .	2.4
3- 6	118.9	0.262	2.165	2.914	1.346	124.5	. .	5.6
3- 7	127.2	0.247	2.420	2.711	1.120	124.1	3.1	. .
3- 8	126.8	0.248	2.463	2.673	1.085	123.9	2.9	...
3- 9	126.9	0.247	2.556	2.705	1.058	127.1	. .	0.2
8- 1	102.9	0.297	1.752	2.755	1.572	103.9	. .	1.0
8- 2	106.7	0.288	1.827	2.766	1.514	107.7	. .	1.0
8- 3	108.0	0.285	1.880	2.769	1.473	110.1	. .	2.1
8- 4	112.1	0.276	1.954	2.777	1.421	113.0	. .	0.9
8- 5	113.8	0.272	2.011	2.766	1.375	114.8	. .	1.0
8- 6	114.3	0.271	2.058	2.745	1.334	115.9	. .	1.6
8- 7	117.2	0.265	2.113	2.739	1.296	117.2	0.0	0.0
8- 8	120.5	0.259	2.166	2.750	1.270	119.0	1.5	. .
8- 9	121.6	0.257	2.216	2.739	1.236	120.4	1.2	. .
8-10	115.2	0.269	2.244	2.627	1.171	118.0	. .	2.8
8-11	110.5	0.279	2.265	2.541	1.122	116.2	. .	5.7
8-12	111.5	0.277	2.307	2.520	1.092	116.6	. .	5.1
8-13	122.6	0.255	2.381	2.623	1.102	121.0	1.6	. .
8-14	125.8	0.249	2.417	2.641	1.093	122.1	3.7	. .
8-15	122.8	0.255	2.446	2.565	1.049	120.4	2.4	. .
8-16	123.8	0.253	2.506	2.607	1.040	123.3	0.5	. .
8-17	125.6	0.250	2.558	2.616	1.023	124.6	1.0	. .
							46.9	47.5
23- 1	125.8	0.249	1.887	1.711	0.907	....	...	...
23- 2	130.6	0.241	2.040	1.692	0.829	....	...	...
23- 3	137.7	0.230	2.342	1.625	0.694	....	...	...
23- 4	137.0	0.231	2.516	1.584	0.630	....	...	...
23- 5	143.1	0.223	2.804	1.553	0.554	....	...	...
23- 6	145.0	0.220	3.158	1.464	0.464	....	...	...
14- 1	73.7	0	2.704	1.970	0.729	....	...	...
14- 2	80.7	0	2.832	2.123	0.749	....	...	...
14- 3	79.3	0	3.138	1.986	0.634	....	...	...
14- 4	78.9	0	3.402	1.891	0.556	....	...	...
14- 5	80.4	0	3.760	1.820	0.484	....	...	...

improvement is hardly enough to be significant, but it may be noted that in 34 of the 44 runs, the fit is improved. Equations (14) and (15) must be regarded as tentative until a larger number of more accurate measurements are available. It is entirely possible that an equation of different form would fit the data better. But it seems quite certain that the resistance law is different in ultra-rapid flow than in rapid, and that in the former, C depends upon the Vedernikov number.

Acknowledgments--The author thanks V. V. Vedernikov and Garbis H. Keulegan for letters which have been of assistance to him, but he is alone responsible for any errors of interpretation.

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THE PERMANENT WILTING PERCENTAGE AS A REFERENCE FOR THE MEASUREMENT OF SOIL MOISTURE

F. J. Veihmeyer and A. H. Hendrickson

Abstract--Soil moisture as usually reported as a percentage on a dry-weight basis without reference to some standard or base for comparison is of limited value. Arbitrary definitions of the kinds of water in soil convey only qualitative ideas. It is shown that the permanent wilting percentage is remarkably constant and that in regions of rainless summers this moisture condition is reached year after year in the soil below the surface layer which is affected by surface evaporation. Soil-moisture extraction curves slope downward approximately uniformly until the permanent wilting percentage is reached. Then the curves continue nearly horizontal. The soil moisture is slowly reduced to a minimum which is slightly below the permanent wilting percentage. The permanent wilting percentage is a satisfactory reference point from which the amount of readily available water and also the amount needed to raise the soil to its field capacity may be calculated.

For many years, hydrologists, soil scientists, and others have been attempting to determine a suitable base from which soil-moisture contents may be reckoned. Soil moisture, unlike other properties of materials, is almost universally determined as mass of water per unit mass of dry soil. The ratio of water to dry soil, without reference to some standard or base for comparion, is, in itself, of limited value. A soil may have a high moisture content, either expressed as a percentage on a dry weight basis or as a ratio of volume of water to unit volume of dry soil; yet it will not be known whether the soil contains water which is available to plants or whether additional water can be stored in it.

In the report of the Committee on Physics of Soil Moisture for the year 1934 [Trans. Amer. Geophys. Union, 1934, pp. 302-312], some of the so-called soil-moisture constants in use were discussed in detail by various investigators in the field of soil moisture, and this report is referred to for the details regarding the opinions held at that time as to the suitability of these various moisture properties. Arbitrary definitions of the kinds of water in soils, such as free or gravitational, hygroscopic, capillary, and so forth, only serve the purpose of conveying qualitative ideas.

Measurements of soil moisture usually are made for one or more of the following reasons: to find the amount of water in the soil; how much water must be applied to raise it to its field capacity; how much is available to plants; and how tightly the water is held by the soil.

Measurement of the amount of energy required to remove unit mass or volume of water from a soil will indicate whether the water is available or not if the correct value of the potential of the soil moisture at the permanent wilting percentage is known. If the measurement of the amount of water in the soil is required, each soil must be calibrated with the particular device used to measure the potential. We have found that taking samples of the soil with a properly designed soil tube is the only practical device under severe conditions. Experience has shown that probably the best soil-moisture constant from which to calculate moisture conditions is the permanent wilting percentage. This term was suggested by us as a substitute for the term, wilting coefficient, by BRIGGS and SHANTZ [1912]. The latter defined the term in such a way that it implied a constant relation between the residual moisture content in the soil at the time plants permanently wilted, and the moisture equivalent. Since it has been shown [VEIHMEYER and HENDRICKSON, 1928] that the ratio of these two values is not constant, the term, coefficient, leads to false implications. The term, permanent wilting percentage, means the actual moisture content in the soil at the time plants permanently wilt.

Some of the difficulties in obtaining an agreement between field and laboratory trials of the permanent wilting percentage have been discussed in a recent paper [HENDRICKSON and VEIHMEYER, 1945]. The appearance of the indicator plants (sunflowers) which may be used to determine the permanent wilting percentage was illustrated so that a definite condition of wilting can be selected to correspond with permanent wilting. It is pointed out that the permanent wilting percentage is not an unique value, but is a small range of soil-moisture conditions within which

permanent wilting takes place. The limits within which the value may be determined are given as about one per cent for fine-textured soils and 0.5 per cent for coarse-textured ones. The fact that in small containers there is a continued extraction of moisture from the soil after the plants permanently wilt has suggested the use of the terms "wilting range" and "ultimate wilting percentage" [FURR and REEVE, 1945; TAYLOR, BLANEY, and McLAUGHLIN, 1934; TAYLOR and FURR, 1937]. The ultimate wilting percentage is defined as the moisture content of the soil at the time all the leaves of the indicator plant are wilted. Since there is a considerable amount of water taken from the soil in small containers by the plants after they have permanently wilted, it has been suggested that the permanent wilting percentage of soil in the field does not represent the lower limit of available water, nor can the permanent wilting percentage be considered to be the minimum moisture content soils will likely have in the field.

The data previously presented [HENDRICKSON and VEIHMEYER, 1945] show that soil-moisture extraction curves plotted from results with plants under field conditions, slope downward approximately uniformly until they reach a moisture content at which there is a marked reduction in rate of extraction. This change in direction of the curve occurs slightly above the permanent wilting percentage obtained from sunflower plants in containers. After reaching this moisture content the curves, from results in the field, continue nearly horizontal, showing that the soil moisture is slowly reduced to a minimum which is slightly below the permanent wilting percentage. This reduction is small, often not more than one per cent, even after three or four months.

No explanation why plants in containers reduce the soil moisture to a greater extent than that found in the field is offered. While it is a fact that the difference in soil moisture between the permanent wilting percentage and the ultimate wilting point when plants are grown in small containers is comparatively large, the difference between the permanent wilting percentage and the minimum soil-moisture contents under field conditions is very small, except, of course, in the top foot of soil where evaporation directly from the soil surface will reduce the moisture content below the permanent wilting percentage.

The conclusion as to the extent of exhaustion of the soil moisture in the field must be based upon empirical trials. We have found that the permanent wilting percentage is remarkably constant and that in regions of rainless summers this moisture condition is reached year after year in the soil below the surface layer which is affected by surface evaporation.

ESSELEN [1937] showed that during the rainless season in the unirrigated portions of citrus orchards, the soil-moisture contents are quickly reduced to a moisture condition corresponding to the permanent wilting percentage, and that they remain at this percentage for very long periods, until the soil is again wetted. Work of others [BRIGGS and SHANTZ, 1912; BURR, 1914] gave a similar result in that the soil-moisture-extraction curves below the surface layer of field soils are essentially horizontal during the latter part of the growing season when the readily available soil moisture has been exhausted. We have used the term readily available water to mean that between field capacity and the permanent wilting percentage, because we believed that some water must be available to plants even though the soil is at the permanent wilting percentage, and that there must be some extraction of water below this moisture content and that, therefore, the soil-moisture curves would show a slight downward slope. We now think that the reduction of moisture below the permanent wilting percentage is very slight below the surface layer affected by evaporation, and that the moisture extraction curves are essentially horizontal after this moisture content is reached.

The figures of this paper give the moisture histories for various types of vegetation and several kinds of soils. All of these records were taken in localities with practically no rain during the growing season, and since no irrigation water was applied, there was a long period during which the extraction curves could be followed without interruption due to rewetting the soil. The records shown in Figure 1 were taken from a steep hillside of gravelly soil of old valley-fill material (Corning) which supported a dense growth of Manzanita with some pine and scrub oak. A rain previous to the sampling on May 5 caused an increase in moisture. Some of the irregularities in this record are due to the large amount of gravel encountered in sampling. It is clear, however, that from July 17 until September 27, which was the date of the last sampling before the rains started, the extraction curves are almost horizontal.

Figure 2 gives the record of a hillside covered with chamise and some Ceanothus and Manzanita. A rain just before May 6 raised the moisture content of the top foot of soil. After July 17 the curves show no further extraction from the upper three ft of soil. On this date, the permanent wilting percentage, about ten, was not quite reached in the three- to four-foot depth.

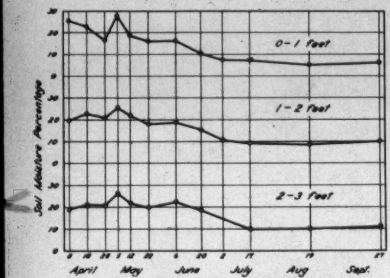

Fig. 1--A gravelly old valley-fill soil, Corning covered with a dense growth of Manzanita interspersed with some pine and scrub oak.

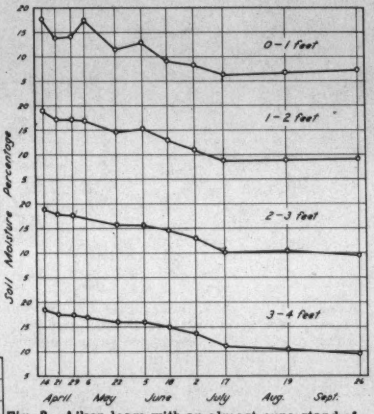

Fig. 2--Aiken loam with an almost pure stand of chamise, but with some Ceanothus and Manzanita

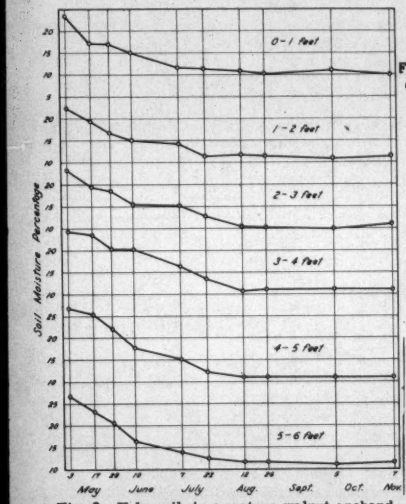

Fig. 3--Yolo soil, in a mature walnut orchard

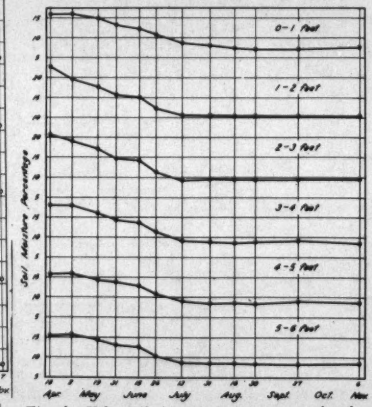

Fig. 4--Yolo soil, in a mature prune orchard

Figure 3 shows the soil moisture in a walnut orchard on Yolo soil. The permanent wilting percentage was reached in the second foot on July 22, and in the lower depths on August 12. No further extraction is indicated after this date.

The prune orchard record given in Figure 4 on Yolo soil is similar to that from the walnut orchard. Here there was practically no extraction after July 13.

Figure 5 illustrates the statement previously made that the permanent wilting percentage is a moisture content reached year after year. The permanent wilting percentage was reached in the top six ft in both years between July 18 and July 31; that in the six- to nine-ft depth in 1934 on July 18. Some water from rain had penetrated below six ft during the early months of 1934 and again in 1935 there was some water below six ft. In the nine- to 12-ft layer in 1934, there was a slight

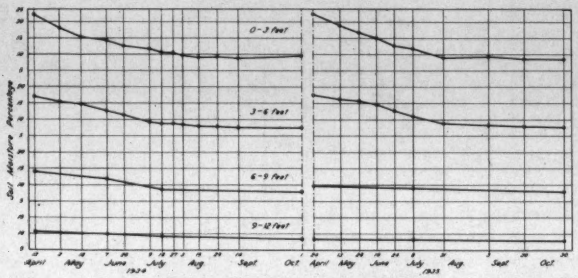

Fig. 5--Yolo soil, in a peach orchard

amount of water above the permanent wilting percentage at the time of the first sampling on April 13, but this was exhausted some time after July 18. There was no replenishment during the rainy season of 1934-1935; consequently, the moisture remained at the permanent wilting percentage throughout the growing season.

Figures 6 and 7 are from a series of grass plots at Davis during 1946. The plots were at different locations with slightly different soil, but the rainfall was insufficient to wet to the full depth of six ft. They are similar, however, in showing that the extraction of moisture ceased at about the time the samples were taken on June 29.

These records together with those previously cited [HENDRICKSON and VEIHMEYER, 1945] show that the moisture-content curves of soils in the field, at least below the surface foot, slope

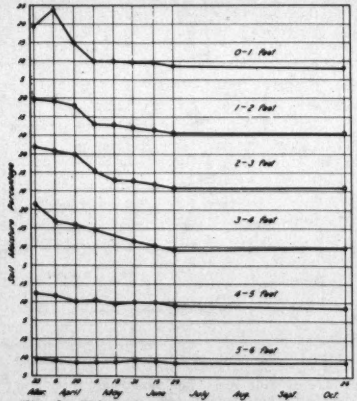

Fig. 6--Yolo soil supporting a growth of soft chess, bur clover, and Nodding stipa

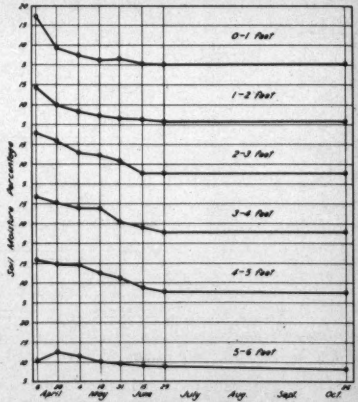

Fig. 7--Yolo soil supporting growth of weedy annuals and Nodding stipa

downward approximately uniformly until they reach a moisture content at which there is a marked reduction in the rate of extraction. This change in direction of the curve occurs slightly above the permanent wilting percentage, but after reaching it, the curves continue nearly horizontal. The soil moisture is slowly reduced to a minimum which is slightly below the permanent wilting percentage. The permanent wilting percentage is a satisfactory reference point from which the amounts of readily available water and also the amount needed to raise the soil to its field capacity may be calculated.

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DISCUSSION

V. S. Aronovici (United States Soil Conservation Service, Pomona, California)--The presentation would be more complete had the authors included permanent wilting percentages of soil depth intervals, based upon sunflower measurements and profile descriptions of sites.

The study does not show by field evidence that most plants are capable of extracting the same amount of water from the soil. The assumption that universal wilting point exists is due, perhaps, to the very narrow range of moisture percentage above ten atmospheres tension. Field application of such a reference point may, therefore, be practical but has no sound basis.

The permanent wilting percentage as described does not consider the nature of the soil solution. In the presence of small to large concentrations of dissolved salts, plant wilt will occur under different moisture percentages.

Plants respond directly to moisture stress created by capillary potential of the soil and the nature of the soil solution. Could not a more effective standard be established on the basis of a specific stress level? Such values may quickly be measured and duplicated in the laboratory. The shape of a soil-desorption curve reflects important soil-moisture characteristics. A standard reference point on this curve would be of great value.

R. F. Daubenmire (State College of Washington, Pullman, Washington)--I am not yet convinced that the concepts of wilting range and ultimate wilting percentage have any general significance. The important point on the scale of diminishing soil moisture is when plant tissues, rather than the soil, become the primary source of transpired water. Although not all plants have organs of such a texture as to reveal a sharp reduction in turgidity, all plants rooted in the same soil appear to experience a physiologic crisis simultaneously when the permanent wilting percentage is attained. Behavior subsequent to this point is exceedingly varied. Certain species die within a few hours; others endure years without replenishment of their moisture supply. Because of this variation in species behavior subsequent to the attainment of the permanent wilting percentage, the wilting range and ultimate wilting percentage differ among species and consequently lack general significance.

In my studies of soil moisture at high altitude it has become apparent that temperature has a very important effect upon soil-moisture constants. Work under way on this problem indicates that generalized discussions of soil-moisture constants, such as the paper by Veihmeyer and Hendrickson, must be broadened if they are to fit field conditions in cold climates.

E. S. Degman (United States Bureau of Plant Industry, Soils, and Agricultural Engineering, Medford, Oregon)--The curves indicate that these plants used very little water during the last 2-4 months of the growing season. Are transpiration records available to show if the trees used any appreciable amount of water during this period? If the trees did use an appreciable amount of water, the source of this water is not apparent in the charts. Would the presence of another source of water influence the slope of the soil-moisture curves?

Joel E. Fletcher (United States Soil Conservation Service, Tuscon, Arizona)--Veihmeyer and Hendrickson seem to have further substantiated some of their earlier proposals, namely, that the permanent wilting percentage can be used as a means for estimating the amount of water needed to raise the soil moisture to field capacity. Observations in Arizona seem to be in agreement with their findings. Figure 8 shows a water-use curve for pinto beans at Flagstaff, Arizona. No rain fell during this period. The point at which the curve flattens out corresponds to the permanent wilting percentage for this soil. On a number of occasions I have had an opportunity to use their concept and have found it very useful.

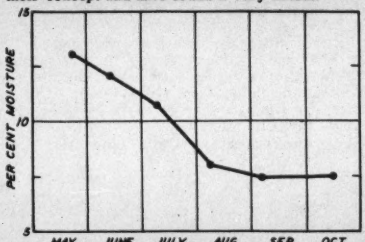

Fig. 8--Water use by pinto bean plants at Flagstaff, Arizona

I. R. Furr (United States Bureau of Plant Industry, Soils, and Agricultural Engineering, Indio, California)--It seems possible that the results reported in this paper may not constitute a critical test of the thesis that the permanent wilting percentage (PWP) rather than the ultimate wilting point (UWP) represents the lower limit of soil moisture available to plants in the field. In laboratory estimates of the UWP, plants are protected from rapid desiccation during the process of wilting to provide for a prolonged period of water absorption at high-water deficits of the plant. In the field, the lowest possible moisture percentages probably are not attained if plant-water deficits are not prolonged and so severe as to cause desiccation and death of most of the plant top. These conditions may not obtain in soils occupied by perennials if some deep roots extend to soil that remains moist throughout the dry season, or in soils occupied by shallow rooted annuals if conditions favor rapid desiccation and death of the plants after wilting begins.

In soils with a PWP of about ten, the wilting range amounts to only two or three per cent, so the relation of the minimum moisture values shown on the extraction curves to the PWP and the UWP seems uncertain.

Willard Gardner (Utah State Agricultural College, Logan, Utah)--It seems to be implied in various places in the literature of soil physics that the vdp term in the expression for the thermodynamic potential (or free energy) represents energy. It should be pointed out, however, that for an incompressible fluid the pressure may be increased without any energy at all. Furthermore, to take a very simple case, the gravitational field acting on unit mass in a tall column of water in equilibrium is equal and opposite to the ratio of the gradient of the pressure to the density, and the gradient of the scalar ϕ, defined thus, $\phi = p/\rho + gh$, vanishes.

I believe it should be observed also that it requires vastly more energy to evaporate a g of water than it does to lift it a distance of 476 ft, corresponding to a pressure of 16 atmospheres. It seems to me therefore that it is not a shortage of energy that causes the wilting of the leaves of the plant.

I. L. Haynes (Ohio Agriculture Experiment Station, Wooster, Ohio)--As long as the permanent wilting percentage is defined as a property of the soil, and not as a property of the plant, it would seem to serve as a useful reference point for measurement of soil moisture. It should be clearly understood that reduction in rate of soil-moisture depletion, as the permanent wilting percentage is approached, is normally due more to the increasingly low conductance of unsaturated soil than to any lack of tension gradients appropriate for movement of moisture from the soil into the plant roots.

Omer I. Kelley (United States Bureau of Plant Industry, Soils, and Agricultural Engineering, Ft. Collins, Colorado)--This paper points out the importance under general conditions of the wilting percentage as a measurement of soil moisture. It stresses and gives data on the extra importance of this soil-moisture constant for non-irrigated soils. I am in complete agreement with the importance of the permanent wilting percentage as indicated by the authors. I believe, however, in their eagerness to point out the importance of this soil-moisture constant that a misinterpretation might be had from part of the paper. This is especially true for irrigated soils. I refer mainly to the availability of water held at soil moisture stresses below that equivalent to the permanent wilting percentage. As is well known, there has been considerable research and publications on the importance of the availability of the water between the range of so-called field capacity and permanent wilting percentage [such papers as C. H. Wadleigh's, The integrated soil-moisture

stress upon a root system in large container of saline soil, Soil Science, v. 61, March, 1946; and references in that paper]. Such information is of special importance under irrigated conditions. It is well known that the wilting percentage is only one point on soil-moisture stress curves giving this relationship.

Don Kirkham (Iowa State College, Ames, Iowa)--I agree with the authors that the permanent wilting percentage (PWP) appears to be a suitable soil-moisture base. That living plant roots tend to remove soil water down, or boost it up to this certain definite moisture percentage, but not beyond, has been hypothecated by Magistad and Brezeale and verified with culture pots by Magistad, Brezeale and Crider [see Tech. Bull. 25, 1929; 29, 1930; 53, 1934, University of Arizona Agriculture Experimental Station], and more recently by Hunter and Kelley [Soil Sci., v. 62, pp. 441-450, 1946]. Veihmeyer and Hendrickson now present conclusive field data to verify the behavior of plants. Besides the remarkable flatness of the curves, one notes that the leveling off occurs at moisture percentages almost invariably lower as the depth of sampling increases. This same condition also occurs in 28 out of 37 cases presented by Veihmeyer and Hendrickson in Plant Physiology, v. 20, pp. 517-539, 1945]. This may be due to increased soil density and attendant decrease in root density. As roots do not penetrate soil at too high a density the PWP then becomes meaningless [Veihmeyer and Hendrickson, Soil Sci., v. 62, pp. 451-456, 1946]. The 15-atmosphere moisture percentage of Richards and Weaver [J. Agr. Res., v. 69, pp. 215-235, 1944] appears to be a good measure of the PWP. Instruments need to be developed to take osmosis into account at the PWP as plant roots surely do.

H. J. Lutz (Yale University, New Haven, Conneticut)--The main thesis of the paper is certainly sound and I believe that it is accepted by the great majority of soils workers. I am not convinced, however, that there is any real advantage in substituting the expression permanent wilting percentage for wilting coefficient. It is said that---"the permanent wilting percentage is different from the Briggs and Shantz wilting coefficient because by definition the wilting coefficient bears a definite relation to the moisture equivalent." On page 9 of the Bulletin by Briggs and Shantz' is this statement: "It consequently appears advisable to use a more specific term for the moisture content of the soil corresponding to the wilting point of a plant, and we have employed the term wilting coefficient in this sense in the present paper." On page 74, the following occurs: "Therefore the moisture content at the wilting point can not all be considered as non-available, and the term wilting coefficient has been adopted to indicate the moisture content of the soil at the time of permanent wilting of the plant."

It seems clear that the wilting coefficient as defined by Briggs and Shantz did not necessarily bear any relation to the moisture equivalent.

O. R. Mathews (United States Bureau of Plant Industry, Soils, and Agricultural Engineering, Beltsville, Maryland)--Field determinations of soil moisture at more than 20 locations in the Great Plains for periods up to more than 30 years have been made by the Division of Soils, Fertilizers and Irrigation. Results with small grains in years of deficient or barely sufficient soil moisture confirm the statement of the authors that under crop conditions in the field little moisture reduction takes place after a rather fixed point that they term the permanent wilting percentage, is reached. With the exception of the surface soil which may be affected by direct evaporation, and within the soil zones where roots are well disseminated, the point to which needed moisture is removed appears to be substantially the same regardless of the severity of the conditions under which the crop is growing. A vigorously growing grain crop that exhausts the soil moisture about the time it matures without noticeable drought injury, will reduce the water in the second and third foot sections of soil to substantially the same point as a crop that goes through a long period of water deficiency prior to harvest. Moisture above the permanent wilting percentage appears to be rather readily available. At least, there is no prolonged period of reduced rate of use as the permanent wilting percentage is approached. This is illustrated by figures in Department Bulletins No. 1004 and 1139 and Technical Bulletin No. 637 of the United States Department of Agriculture.

L. A. Richards (United States Bureau of Plant Industry, Soils, and Agricultural Engineering, Riverside, California)--Soil salinity is not ordinarily mentioned in connection with the permanent wilting percentage as the latter is defined and used in relation to the lower limit of soil moisture observed under plants. The permanent wilting percentage of a non-saline soil is definitely related to the specific surface of the soil, and a relation to surface-force action and soil-moisture tension is thus implied. Preliminary data indicate that the osmotic pressure of the soil solution also can be an important factor determining the lower limit of moisture in soils, and further, that this lower limit under saline conditions will depend on the plant species. An added complication arises from the fact that in saline soils, many plants do not exhibit wilting symptions, or wilting symptoms

are much more difficult to observe. Consequently, the writer would prefer to see permanent wilting percentage not used in connection with saline soil, at least until fundamental relations are further clarified.

The energetics of the permanent wilting percentage are not as yet well understood. This is chiefly due to the fact that precise methods are not now available for measuring, over the whole plant-growth moisture range, the combined effect of soil-moisture tension and osmotic pressure.

S. J. Richards (University of California, Riverside, California)--In several publications, and again in this paper, the authors state that any moisture in the soil above the permanent wilting percentage is readily available to growing plants. Data from supplemental irrigation experiments in the more humid regions are accumulating to show that yields are reduced if soil moisture is not maintained considerably higher than the permanent wilting percentage. Under certain conditions it may be wrong to leave the impression that soil moisture may be depleted to the wilting point before irrigation is applied.

C. A. Van Doren (United States Soil Conservation Service, Urbana, Illinois)--The authors have done an excellent job in calling attention to the importance of establishing and using a base point, such as permanent wilting percentage, above which useable moisture exists in a soil. Expression of soil moisture in quantities available to plants will bring about an acceleration of studies to determine the interaction of climatic and other edaphic factors to moisture in soils.

In the field a plant is capable of maintaining turgor and growth when growing in soil where the moisture content ranges from saturation to below the ultimate wilting percentage. In a study by Reimann, Van Doren, and Stauffer [Reinmann, E. G.; Van Doren, C. A.; and Stauffer, R. S.]. Soil-moisture relationships during crop-production [Proc. Soil Sci. Soc. Amer., v. 10, pp. 41-46, 1945] periods have been found when no moisture is available to corn from the surface to a depth of 3 1/2 ft. The plants under these conditions remained turgid and continued to grow luxuriantly. Undoubtedly the corn roots secured moisture from lower levels in the profile which was exuded adjacent to root hairs, permitting intake of plant food nutrients. This and other phenomena relating to properties of the transpiring plant itself must be given greater recognition in expressing and in studying soil moisture.

H. G. Wilm (United States Forest Service, New Orleans, Louisiana)--In this excellent report, the authors have presented sound arguments for using the permanent wilting percentage as a reference point in agricultural studies. There may, however, be objections to it for other types of experiment. In our Colorado watershed investigations, for example, the field capacity seemed to be better as it could be sampled directly in the field each spring, shortly after the last winter snow had melted. With a cool climate and summer rains, on the other hand, the permanent wilting percentage may seldom be reached under field conditions.

As indicated by the authors of this paper, direct sampling seems to provide the best means for estimating soil-moisture parameters. Aside from the mechanical bias that may be associated with laboratory constants, the regression of field values on them is likely to contain errors large enough to make the results unsatisfactory. As one example from our experiments, we worked out the regression of field capacity on moisture equivalent. Naturally these variables were found to be strongly correlated; yet the errors of estimating field capacity from data on the moisture equivalent were too large to permit the desired precision. Hence, it seemed best to continue sampling field capacity by direct means.

F. J. Veihmeyer and A. H. Hendrickson (University of California, Davis, California)--In summarizing the statements, space does not permit specific reference to each reviewer. We desire to comment only on the points which have been raised against the selection of the permanent wilting percentage as a reference point for the measurement of soil moisture. The purpose of our paper was to bring out data which might indicate the relation of the permanent wilting percentage to the minimum moisture content in place in the field.

In reply to Aronovici's suggestion, we refer to an earlier paper [HENDRICKSON and VEIHMEYER, 1945] where it is shown that the permanent wilting percentage may be obtained by either of two general methods: By indicator plants in containers; or by a system of soil sampling during the growing season. He raises the question whether different crops will remove the moisture to the same level. An example of the constancy of the permanent wilting percentage is illustrated by the fact that guayule following prune trees reduced the soil to the same minimum moisture content. Sugar beets, tomatoes, and alfalfa planted in the same field where the guayule and prune trees had been growing had permanent wilting percentages which corresponded with those for these

crops and with permanent wilting percentages determined with sunflowers. In answer to Aronovici's desire for a reference point on the soil-moisture-extraction curve, we point out the fact that the permanent wilting percentage is the moisture content at which the curve becomes nearly horizontal and, therefore, is a good reference point.

In answer to Degman's question, attention is called to the fact that the trees and perennial crops, for which the moisture data are recorded in our paper, did not die. They, therefore, must have obtained some water either at a very slow rate at the depth of soil sampled (for which the means of measurement at hand were not precise enough to determine) or below these depths, and yet the soil moisture-extraction curves are substantially horizontal after the permanent wilting percentage was reached.

Replying to Furr's comments, we have stated that the permanent wilting percentage is not an unique value, but is a small range, and that under field conditions the moisture curves slope downward about uniformly until they reach a moisture content at which there is a marked reduction in extraction. This change in direction of the curve is slightly above the permanent wilting percentage obtained with sunflowers in containers. This change, furthermore, in direction, is not the first sign of wilting, but corresponds to a definite condition of the plant from which it will not revive unless water is added to the soil. Our experience is that when wilting begins, the plant revives in a moist chamber without the addition of water to the soil. After the marked change in direction of the moisture-extraction curve in the field, it remains nearly horizontal. For reasons as yet unknown, the minimum moisture percentage that may be reached in the field is higher than that obtained when small containers are used. The difference between the permanent wilting percentage and the minimum moisture content found in the field is small at best.

The variations of the permanent wilting percentages with depth, to which Kirkham refers, we believe, have no significance except to indicate a change in soil and are probably due to textural differences.

Lutz objects to the term, permanent wilting percentage. We were reluctant to use this term in preference to the wilting coefficient, but in order to be certain that the actual moisture content in the soil at the time plants permanently wilt is meant, and not a calculated value, the former term was selected. The term coefficient is the one which may cause some misunderstanding, and necessitates a statement in each case whether the value is experimentally determined or calculated from other values such as the moisture equivalent.

We did not intend, in our paper, to include a discussion of the effect of various soil-moisture conditions upon the growth of plants, since we were concerned only with the permanent wilting percentage as a measurement of the minimum moisture content reached in field trials below the surface layer, but Kelley and S. J. Richards raise a question concerning growth and soil-moisture content Our experiments show that the maintenance of high moisture contents does not result in high yields. Reference to our work on deciduous fruits and vines as well as that of others working with different kinds of plants [see all "References" below], substantiates our statement that soil moisture between the field capacity and the permanent wilting percentage is readily available.

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SOME SEMANTIC ASPECTS OF HYDROMETEOROLOGICAL RESEARCH

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Abstract--This paper deals with general concepts and processes of observation, description, and interpretation. The semantic approach depends largely upon the ideas of KORZYBSKI [1942], in which are emphasized the abstracting of particular attributes to form higher orders of abstraction. Examples from hydrometeorology illustrate the importance of differences between orders of abstraction. BRIDGMAN'S [1932] operational definition is discussed and advocated. Analysis is presented as a refining of description, with emphasis on preserving the structural features and thing-as-a-whole attitude toward a subject of study.

Introduction--The term "semantics" orginally referred to the study of the meanings of words. More recently [KORZYBSKI, 1942], its scope has broadened to include the science of the meanings of symbols generally, the structure of expression, and the study of mental processes. As indicated by KORZYBSKI [1942]; ODGEN and RICHARDS [1936]; CHASE [1938]; and HAYAKAWA [1941], an important feature of semantics is the concept of "order of abstraction." Events and objects are regarded as basic, and attributes or characteristics abstracted from them are labeled by words and other symbols, which are known as higher order abstractions. BRIDGMAN [1932] introduced the concept of defining the higher order abstractions in terms of real or imagined operations or processes.

According to Korzybski, "all" of an object or event cannot be known, but a limited, and perhaps large, number of characteristics can be observed and abstracted. For example, from the vast event known as a storm, there may be abstracted a characteristic or element, say, precipitation. The precipitation might be sampled by catching some of it in a can. If several such observations are made, they might be represented by symbols on recorder charts, which could further be abstracted in the form of digits, and their mean value would be a useful high order abstraction. A still higher abstraction would be an estimate of the mean depth of precipitation over a particular drainage basin. The object or element represented by a symbol is termed the "referent" of the symbol by Ogden and Richards. Straight thinking requires careful distinction between referents and their symbols, also consciousness of the relations between them.

Korzybski and other rigorous thinkers have emphasized the fallacy of assuming a simple cause and effect relationship. Bridgman has shown how, even in laboratory physics, there is never a single cause of a single effect. There are always ambient conditions, and an observation is a product of both the subject of observation, and of the technique of observation. Hydrometeorology deals with the subjects of weather and stream flow, usually involving some effort to relate the two. By way of perspective, hydrometeorology may be classified and contrasted with some other sciences with respect to the degree of freedom in selecting or identifying the elements to study, and in the degree of control over their variation. In hydrometeorology there is seldom much control of either the number of variables or of their variation. A drainage basin must be accepted as it is, and the weather taken as it comes.

By way of further introduction, the following list shows in a general way the order of steps involved in a hydrometeorological project: (1) A recognized need for an investigation, (2) authority and commensurate responsibility for performing the work, (3) a plan for the project, (4) observation of various elements and phenomena, (5) description of, or distinction between, the things observed (6) classification and comparison of the data, (7) combination of the data by functional relationships, (8) a report or other product, (9) review of the report or other product, (10) trial or verification of the product, (11) operational application. To some extent this paper follows the foregoing list.

A plan for the project--Without wishing to introduce an argument about definitions of such high-order abstractions as "science," "truth," or "knowledge," especially any of the foregoing "for its own sake," it is assumed that the hypothetical project has a rather specific and definable purpose. The purpose is to influence action. This requires foresight and deliberate thinking about the nature and application of the resulting product.

A project plan should include not only the selection of a site, personnel, and instruments, but also should anticipate the manner in which observations are to be made and analysed. FISHER [1936 and 1937], SNEDECOR [1940], and other statisticians have written much on the subject of design of experiments. Seldom are observations worth the bother or cost of taking unless a relation of some kind is expected, and unless they are taken at such times and places as to enable them to be functionally related.

As early as possible, even if subject to possible change as the project develops, the final product should be specified, be it a report, a map, or a process; and it is helpful if the product is described in optimum detail, appropriate to current knowledge or requirements. In specifying and appraising the final product, several criteria may be considered, including: (1) Relation of the project to, and possible change in, its administrative and its scientific environment; (2) degree of gain over present knowledge or situation; (3) point of diminishing returns; and (4) appropriateness of the product to its purpose and its origin. One feature of appropriateness is that the data, the final product, and its application should have corresponding and optimum precision. In evaluating the final product, a trial run or independent verification is the only assurance of reliable knowledge.

Observations--Observations must be regarded as fundamental, as they are our sole source of information from "outside our own skin," to use Korzybski's words. Ideas, thought patterns, hypotheses, and theories are abstractions or combinations of abstractions of earlier observations. According to JAMES [1907], truth is not an inherent characteristic which can be sought, or which establishes a framework into which data must be fitted. Instead, "the truth" of an idea is determined by its practical consequences. The criterion of "validity," "truth," or "reality" is in the observation of an action or object.

It may be instructive to apply Bridgman's operational definition and the concept of order of abstraction to the observation of two well-known meteorological elements. Much has been written on the subject of rain gages; for example, the work of ABBE [1899]. The issue of adequate performance involves the concept and definition of "true catch." What is the true catch? Bridgman says a question is meaningless unless an operation or process can be performed or imagined which will provide the answer. Many ingenious installations have been contrived to provide a pragmatic and operational determination of true catch. One such gage [KOSCHMIEDER, 1934], simulates the reception of rain actually reaching the ground by placing the gage in a shallow pit. Around the top of the gage, and level with the surrounding ground surface is a coarse screen, which is intended to provide a minimum of unnatural effect of spattering, air movement, and other influences. Such an installation is too expensive and requires too much expert care for routine use. The prospect of water running along the ground, water spattering up from the ground, possible growth of weeds, and accumulation of snow on the ground, are reasons for regular rain gages to project up from the ground. The obstruction of a rain gage into the path of the rain-bearing air stream influences the portion of the rain which becomes separated from the air in which it is traveling.

In calibrating a regular gage against an ideal or standard gage, it is impossible for the two gages to measure the same increment of rain, or to occupy identical sites. The comparison is affected by the varying and unknown influence of rugged topography and nearby trees or other vegetation. Thus, in abstracting a sample of rain by means of an ordinary gage, there remains the irregular areal distribution of rain within the storm, also the unknown variance due to local exposure. In catching snow the problem becomes even more complicated, and, without laboring the point, the rigorous conclusion is that no true catch has been or can be reproduced. There is little doubt that the actual catch is usually of the same order of magnitude as the true catch would be, were the obstructing gage not there. However, at the observational level, there is necessarily a varying and unknown relation between the actual catch and the true catch. The actual catch is a joint product of the true catch, the environment in which the sample is taken, and the characteristics of the instrument. Possibly the only effective purpose of improving precipitation gages is to stabilize the so-called index relation. Some instruments have a relatively stable index relation if their characteristics tend to minimize the effects of the uncontrolled and varying environments.

The observation of air temperature does not require the catching of a sample, but depends on the functional relationship between temperature, whatever it is, and its indication by an instrument. Air temperature can be defined operationally and pragmatically in terms of heat exchange, which appropriately is the source of interest in temperature. The phenomenon by which an instrument indicates temperature may be the differential expansion of mercury and glass, electrical resistance, or some other dependable relationship. To reduce the effects of radiation and other products of the environment the thermometer is provided with a shelter and with ventilation. The

ventilating air continually changes its identity and its source. Therefore the changing sample of air passing through the shelter has its temperature integrated, both in time and space, and the abstracted observation is sort of a running mean.

Without describing more examples, the point to be emphasized is that observations are abstractions of more fundamental events, and the relations, while frequently useful and dependable, are, and must remain, unknown.

While the subject of negative evidence is somewhat of an anticlimax to the important conclusion stated above, it is a striking example of confusion of orders of abstraction. Negative evidence is a term describing the lack of a report as indicating a lack of what is to be reported. For example, no report-of-precipitation might possibly be interpreted as evidence of no precipitation. Of course such a conclusion lacks rigor, and adequate reporting includes specific reporting of zero values. The report is a different and higher order of abstraction than the observation.

To proceed further with the subject of orders of abstraction, observations requiring conversion or rating tables, such as stage to discharge, involve an additional abstracting operation. Similarly, the conversion of an autographic record to useful numbers involves an abstraction. This operation usually is either an integration or summation by totals or means for somewhat arbitrary periods of time, or a sampling of ordinates at (regular) intervals.

In addition to the physical subjectivity of instruments there is the personal subjectivity of the observer. In astronomy and precise surveying, the personal factor is recognized and its influence reduced by averaging a number of observations or by actually computing the personal equation. In hydrometeorology, however, subjectivity is tolerated to considerable degree. One form is the variable personal judgment in identifying and describing clouds. In observing the water equivalent of snow on the ground from time to time, it is obviously impossible to take more than one sample from the same place, and the environment varies, more or less, for successive samples taken "near" the same place. Further, when the physical nature of the snow makes the getting of a "good" sample uncertain, it is not uncommon for the observer to choose one of several samples, and to report only that one. The personal factor becomes increasingly important and variable as conditions of observation become difficult, as from fatigue or from particularly uncomfortable weather.

As observation merges into description and classification, the distinction between orders of abstraction should be preserved. An observer should report what he observes, and not substitute for it a higher order abstraction, such as a conclusion he may have reached. An advantage of abstracting is the resulting simplification, but it is important to remember that in abstracting characteristics from a referent the unabstracted characteristics remain with the referent and distinguish it from its symbol.

Analysis--The term "analysis" usually means the separation, either physically or logically, of component parts of a subject of study, with the implication or purpose of greater ease of examination or better "understanding." By isolation of the components, their individual value, function, and relationship may be clarified. In analytical work symbols are practically necessary. For example, a drainage basin is conveniently represented by means of a map. The elements abstracted and portrayed are the configuration of streams and divides, and the topography, as shown by contours. Other features of the landscape may be abstracted and represented symbolically, but it is important to remember that elements remain which cannot all be shown on the map. To be valid, the map is required to show the abstracted characteristics of the physical land in their correct position. The map should be similar to the drainage basin in the strict geometrical sense. The scale and orientation of the map with respect to its referent are matters of convenience. The one necessity is that of configuration or structure. The map represents the land, not vice versa. Naturally and logically, the higher order abstraction is the product of the lower abstraction. The reverse cannot be true.

In addition to the abstracting process, which deliberately leaves some elements unabstracted, there is the matter of fidelity of projection. Legitimate simplifications, appropriate for particular purposes, may be made. For portraying "large" portions of the Earth's surface on a plane map, a choice is sometimes made between projections having equal area relationships, and projections having other characteristics, such as practically true shape for small areas.

Terrain itself is an abstraction of the events which produce it, being a cross-section, in time, of geological processes. A map might be described as a single frame in the moving picture of geomorphology.

A more general type of symbolic representation than a map, is a mathematical function. Like a map, a mathematical expression deals with structure and relations. It has no physical reality. Its value lies in the degree to which it correctly represents the physical object or event which is its basis. It must be remembered that the events or objects which are abstracted or described by mathematics have innumerable characteristics, many of which are unknown. The abstracting should be done deliberately, with awareness of the leaving out of characteristics. A few examples of characteristics frequently not abstracted are: (1) Air resistance, in elementary computations involving the acceleration of gravity; (2) centrifugal force of the Earth's rotation, in dynamic meteorology; (3) the varying viscosity of turbulent flowing water, in hydraulics; (4) sediment load as a component of the discharge of streams; (5) non-isentropic processes in the atmosphere; and (6) vertical component in the area of a drainage basin. Mathematics may describe not only a static object, as a map describes terrain, but also may describe functional relationships. The functional relationships are frequently more subtle and more complicated than relationships involving position in space. Also, especially in research, less is known about the functional relationships than is known about static features, and simplifying assumptions may be made unwittingly.

In hydrometeorology, the essence of inquiry is usually that of relationships. The interest is in structure and function. The purpose of observing what are separated into elements is to see how they operate together. In "eliminating the variables," as experimenters say, they are abstracting those that are left. In eliminating some of the variables, the functional relationship of the entire aggregate may be disturbed. All the characteristics of a drainage basin cannot be separated and examined individually, and if they could there would still be the problem of reassembling them in proper relation. Certainly a clock is more than the sum of its parts. It is the fitting them together in a unique and very special way. If amenability to prediction of action is a criterion of complexity, it must be admitted that a drainage basin is far more complex than a clock. This leads the discussion to the concept of "thing-as-a-whole," as contrasted with the elemental concept.

An example of the elemental concept is the idea of the hydrologic cycle being composed of individual elements which have physical reality. Consideration of the two elements, evaporation and transpiration, illustrates one of the deficiencies of the elemental concept. Attempts to separate these two elements physically have not been successful, because the artificially altered environment changes their action and their relation. This is discussed in the report of the Committee on Evaporation and Transpiration for 1947 [WILM and OTHERS, 1948].

Another example, and important more than merely as an example, is the concept of infiltration. The idea of basin-wide infiltration as a discrete factor, distinguishable from basin-wide runoff, is an abstraction, which could not have originated from observation, but is a product of imagination. Practically, how would it be determined how much water flows over the soil and how much through it? In rugged basins, water, on its way to the stream, frequently travels intermittently through and over the soil. Even at one spot, classification of water as to surface runoff or sub-surface flow is difficult.

In efforts to isolate a small portion of a large basin for close examination of detailed phenomena devices such as lysimeters have been employed. Aside from all the difficulties, including all the boundary effects, in making lysimeter and plot observations of infiltration, there is the difficulty of giving areal expression to the results. The areal distribution of infiltration is complicated by the areal distribution and the time distribution of soil conditions and of supply of rain and/or melted snow. The areal distribution of soil characteristics, slope, distance to a waterway, the detailed pattern of water supply, and of other related factors have probably never been observed in a basin large enough to warrant neglecting all the boundary effects. In a basin having an area larger than a few acres, complete knowledge of the physical pattern, not to mention the functional relationships within the pattern, would be literally impossible. The problems of sampling and the assumption of a manner in which micro-observations may be combined in area and time are to be emphasized. While, for purposes of training and for development of hypotheses to be tested, the qualitative concept of distinguishable basin-wide infiltration may be convenient, the fact remains that the concept is not based on observed or observable fact. There is a lack of rigor in assuming and defining an unobserved basin-wide abstraction, concluding that it appropriately can be separated from other elements and from its environment, and then integrating this presumed element back into the basin complex. The manner chosen for integration may be as important as the very magnitude assigned the element. The computational process of integrating the hydrologic elements should be similar in structure to the physical processes occurring on the basin-as-a-whole. Techniques such as the unit hydrograph method represent an empirical device for using the basin to integrate its own equation of areal and time distribution.

Objections are sometimes offered to methods which, regardless of how well they may "work," do not provide what is called an "understanding." The term "understanding" is closely related to another term, "explanation." Consideration of some of the semantic aspects of an explanation may be worthwhile. Very often answers to the questions of how and why are little more than playing with words. If it is asked why water flows down hill, and answered that the force of gravity causes it to, there is no increase in knowledge, but merely a substitution of words. Gravity, as a concept, has resulted from the observation of falling apples, flowing water, motions of planets, and other such physical events. A particular feature of these events has been abstracted and given the label "gravity." The concept of gravity has been a product of water flowing down hill, rather than vice versa. An operational definition of gravity would involve such physical processes as water flowing down hill. An advantage of the concept of gravity is its generality, which leads people confidently to interpolate or to extrapolate beyond specific experience. The degree of generality of a concept can be established only by detailed observation within the scope which the observations establish. Colloidal suspension and capillarity are examples which illustrate the limited scope of gravity as a predominating influence.

Instead of being concerned with an abstract "why," would it not be sufficient to accept the "how" or the "what?" The thing to be emphasized is that water can be depended upon to flow down hill, any time and any place, as a literally general characteristic of large streams of water. Instead of answering a question with a word abstracted from the event itself, a more useful "answer" would be, "water 'naturally' or 'always' flows down hill."

The more completely a fact is described, presenting its relations to other facts, the more the description is acceptable as an explanation. As descriptions are made, particularly of relations, the process becomes one of analysis. The description might include the presentation of data in arrays, frequency distributions, double frequency distributions, and graphically portrayed relationships. In an effort to recognize distinct parameters, and still to preserve the integrity of a thing-as-a-whole, modern statistical methods include the descriptive-analytical techniques of analysis of variance, analysis of covariance, and multiple regression. These techniques rigorously avoid the fallacy of a single cause producing a single effect. Also statistics avoids the fallacious keystone of formal logic: The law of the excluded third; by providing the concepts of probability and fiducial limits. Stated simply, the law of the excluded third is that something is either A or not A. "It must be one or the other." But what is meant by is A or not A? The idea is not one of identical equality to A or to not A, as much as it is to include the item under question within a class, A, or outside of it. KORSYBSKI [1942], BELL [1934], and others have written volumes on this subject, and it cannot be given justice here, but to resume the discussion, a class, A, is a higher order abstraction than the items which comprise it, and in abstracting characteristics to define the class, other characteristics are knowingly or not, omitted. Therefore a class rarely accomodates entire objects or items, but merely some of their stated characteristics. The discussion of the whole equalling the sum of its parts, and of water on a basin having to flow either over or through the soil could appropriately be repeated here.

As said before, statistical methods have two purposes, which merge; one is to describe and present material in a comprehensive manner, and the other is to show and evaluate relationships. Statistics can confirm or test a relationship, but can hardly be expected to divine which mathematical model "best" expresses a relationship. Of those models submitted for testing by means of the data, the statistical method will evaluate each, and on comparable bases. Statistical methods involve a trial and error process. Much of their success depends upon the imagination and resourcefulness of the user, who must present hypotheses for testing. Statistical methods do not "work," they must be worked. The analyst must draw upon his experience and that of others for ideas to try. By considering classical theory, analogies, empiricisms, "hunches," and "common sense," an analyst may be said to interpolate within his many-dimensioned continum of knowledge.

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ANNUAL RAINFALL AND RUNOFF IN NEW ENGLAND

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Abstract--This paper presents the results of studies of average rainfall and runoff, developed in the Office of the Division Engineer, New England Division, United States Corps of Engineers, in cooperation with the District Engineer, United States Geological Survey, and prepared in connection with flood-control studies of the Connecticut and Merrimack River basins.

Introduction--Determination of average annual rainfall and runoff is generally one of the first steps in defining the basic hydrology of a region or of individual river basins, but available maps of precipitation do not entirely reflect the effect of elevation or other factors influencing rainfall, owing to the fact that few rain gages are available at high elevations or in remote areas. Runoff data from stream-flow records at United States Geological Survey gaging stations give the total runoff of substantial watershed areas which frequently combine mountainous areas and lowland areas.

The principal factors affecting precipitation are the distance from the source of moisture, the elevation, and the rain shadow or barrier effect, the effects of which may be briefly described as follows: (1) The usual source of moisture is the Atlantic Ocean, because continental and tropical storms produce circulation that draws in moist tropical air from the east and south. The coastal regions close to this source thus tend to receive on the average greater precipitation than the inland regions. (2) The higher elevations that occur inland in the hills and mountains cause lifting and cooling of the moist air masses and, as a result, more moisture is deposited in upland areas, particularly on exposed eastern and southern slopes. (3) The upland areas form barriers to the passage of moisture, with the result that western slopes and valleys receive less moisture than eastern slopes due to a rain-shadow effect.

The effect of elevation on rainfall has been expressed by empirical formulas plus conventional reference to literature. BARROWS [1933] determined for the coastal side of the Green and White Mountains the relation $R = 24 + 7 (A - 1)$ for altitudes above 1000 ft, where R is the mean yearly precipitation and A is the altitude in thousands of ft. This formula indicates an increase of seven inches of precipitation for 1000 ft increase of altitude or about 23 per cent increase from 2000 to 3000 ft.

A relief map of New England shows the country rising gradually from low and level coastal areas to a rugged upland country. The Berkshire Hills in Massachusetts and Connecticut, the Green Mountains in Vermont, and the White Mountains in New Hampshire form sharply defined drainage boundaries of the Connecticut and Merrimack River watersheds. These have a pronounced effect on the rainfall and runoff characteristics of the region. The Green Mountain Ridge has an average elevation of between 2000 and 3000 ft, with a few peaks reaching to 4000 ft above sea level. The White Mountains are lower in southern and central New Hampshire, but in northern New Hampshire they rise above 4000 ft and reach a maximum of 6290 ft at Mount Washington.

Average annual runoff--At the present time there are about 160 stream-gaging stations in the area, one-half of which have been maintained for 15 years or more. In order to place all records on a comparable basis, the shorter records have been adjusted to give an average for the 20-year period 1924-1943. The adjusted values for all stations in and contiguous to the area were plotted on a map having 100-foot contours. Generalized lines of equal runoff were drawn as shown on Figure 1. The lines were adjusted so that the average runoff computed from these lines within a given basin equaled the average runoff for that basin as measured at the gaging stations.

Relation between average precipitation and average runoff--The difference between average precipitation and average runoff is the water loss of a drainage basin. This loss for any given year will be affected by a variation in the amount of water held in storage at the beginning and the end of the year. This effect is minimized by using the water year ending September 30 because usually at this time storage of water in the form of snow or ice, or in ponds, lakes, and

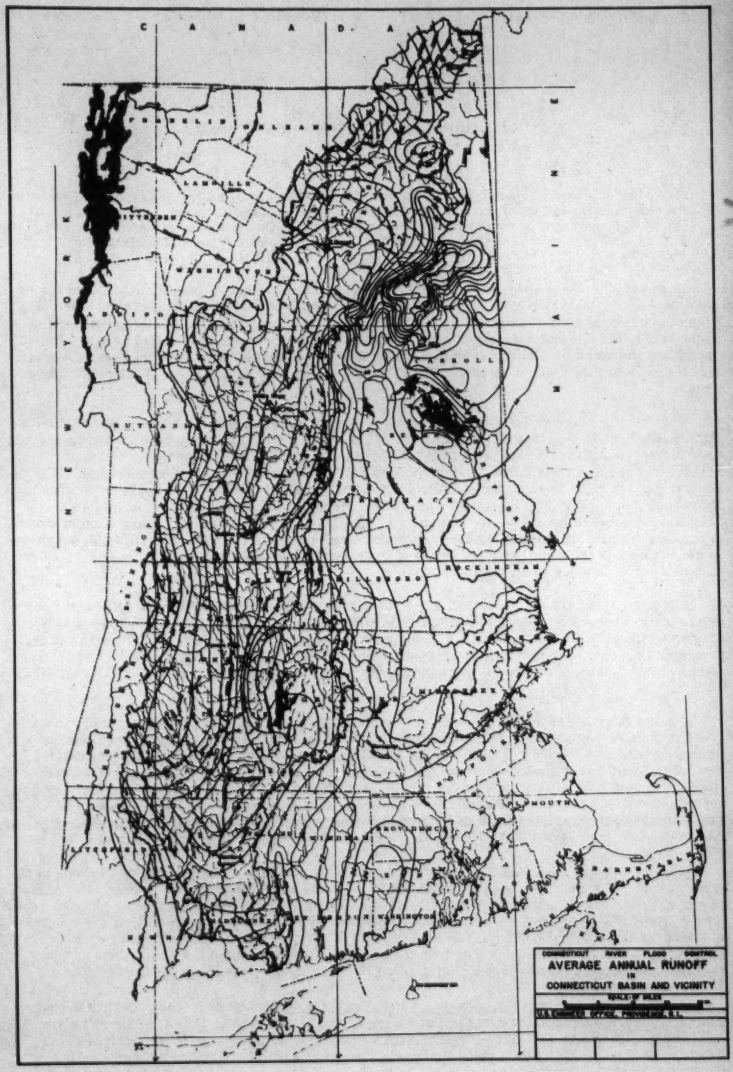

Fig. 1--Average annual runoff in Connecticut Basin and vicinity

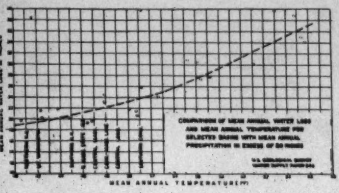

Fig. 2--Comparison of mean annual-water loss and mean annual temperature for selected basins with mean annual precipitation in excess of 20 inches

swamps, or as soil moisture and ground water, is at a minimum. The effect of differences in water held in storage in a drainage area is further reduced by using a mean annual-water loss obtained from an average based on several years record. This average water loss is essentially evapotranspiration .

A comparison of mean annual water loss and mean annual temperature is shown in Figure 2 [from WILLIAMS and OTHERS, 1940]. The plotted points are for selected basins throughout the United States, east of the 104th meridian, with mean annual precipitation in excess of 20 inches. It will be noted that most of the points plot within one or two inches of the mean curve. The maximum departure is 4.5 inches from the curve. Thus, the average water loss obtained from this curve is within ten per cent of individual records used to define the curve.

The water loss may be considered as a relatively stable figure, varying in general with average temperature from about 18 inches in northern New Hampshire and Vermont to 24 inches in the coastal regions of Connecticut. In this study, the water losses obtained from the curve were added to known average runoff to develop average areal precipitation.

Annual precipitation--Approximately 300 precipitation stations within and adjacent to the Connecticut and Merrimack River basins have been maintained by government and private agencies. Not all of these stations are maintained at the present time and the periods of record are variable. Therefore, in order to place all the records on a comparable basis from the standpoint of the period sampled, each record was adjusted to the 25-year period, 1920-1944, inclusive.

Very few records of precipitation at high altitudes are available. Therefore, little is known about rainfall at altitudes above 2000 ft. The records at high altitudes are limited to the stations shown in Table 1.

Table 1--List of high-altitude stations used in this study

Station	Altitude	Period of record
	ft	
Mt. Washington, N. H.	6290	1933 to date
Searsburg Mt., Vt.	2400	1925 to date
Pinkham Notch, N. H.	2000	1925 to date
Peru, Mass.	1700	1920 to date
First Connecticut Lake, N. H.	1660	1920 to date
Heath, Mass.	1650	1920 to date
Glencliff, N. H.	1650	1920 to date
Dixville Notch, N. H.	1650	1931-1939
Middlefield, Mass.	1650	1921 to date
Plainfield, Mass.	1650	1920 to date
Dover, N. H.	1650	1925 - 1930
Wilmington, Vt.	1640	1931 to date
Goshen, Vt.	1630	1930 to date
Searsburg Station, Vt.	1530	1924 to date
Whitingham, Vt.	1500	1923 to date

In preparing the isohyetal map of average annual rainfall shown in Figure 3, the adjusted averages of precipitation stations were plotted on a map having 100-ft contours. To overcome the deficiency in precipitation data for the higher areas, the relation between average precipitation and average runoff was employed. The water losses obtained from Figure 3 were added to the known average runoff obtained at the United States Geological Survey gaging stations to obtain average areal precipitation. Most of the tributary areas had at least one precipitation station located near the mouth or in the low-lying valleys. A comparison of the computed areal precipitation with that for the available station records usually indicated that the precipitation at high altitudes must be considerably in excess of any measured values, and the isohyetals were plotted accordingly. Whenever there were inconsistencies with average runoff and average water losses,

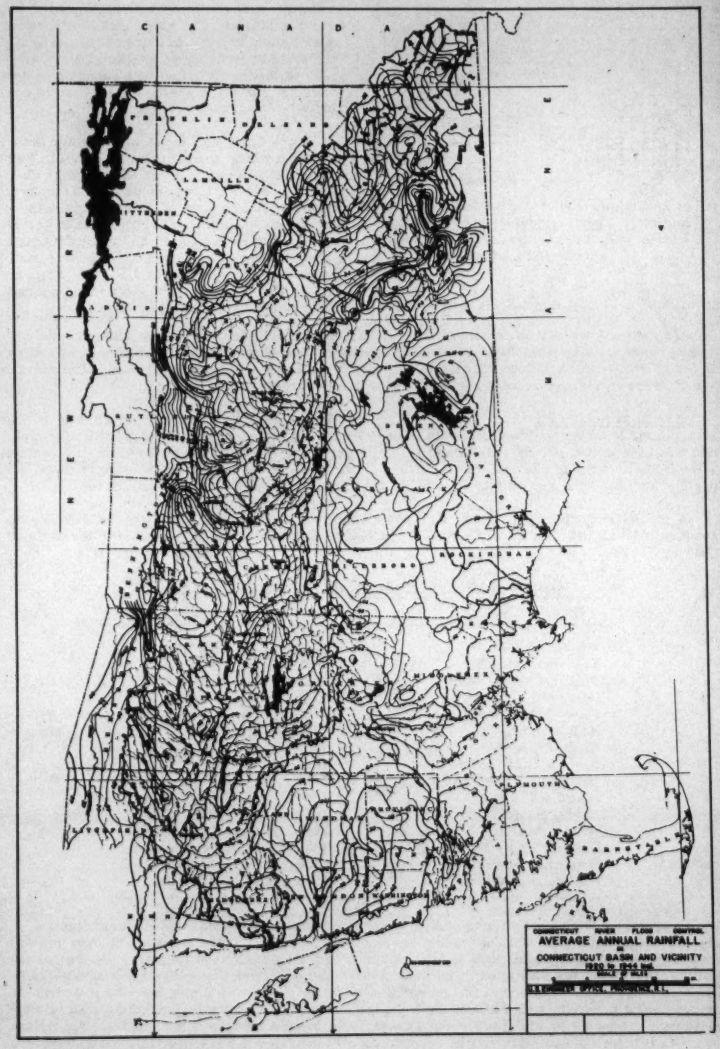

Fig. 3--Average annual runoff in Connecticut Basin and vicinity, 1920-1944

the rainfall was extrapolated from available records. As a further check, altitude-precipitation relations were plotted for different localities and compared with the estimates obtained by the above methods.

Discussion--It is the usual practice in rainfall-runoff studies to extend the runoff records on the basis of rainfall records. This is probably because of the fact that rainfall stations are more numerous than runoff stations and because most rainfall records are considerably longer than runoff records. However, as the precipitation records in the area under study are not adequate in distribution to give areal precipitation, especially at high elevations, it was necessary to devise special means of developing areal precipitation from available data. Consideration was therefore given to the runoff records and water losses.

Runoff is the residual of precipitation after losses. In this region a knowledge of any two of the three elements makes it possible to determine the third. The water-loss figures which were obtained from the general relations are subject to error for individual stations but this is small compared with the errors involved in using only precipitation records. The stream-gaging stations are fairly well distributed throughout the area, although there are none on small areas at high altitudes. The records of yearly runoff are, in general, subject to only minor inaccuracies. Therefore, it was decided that the runoff records are an excellent index of areal precipitation, since they are direct measurements of the net effect of precipitation within the drainage area.

The method used in obtaining the isohyetal map is unique in that runoff records, water losses, and generalized topography, were used in conjunction with precipitation records to obtain areal precipitation. It will be noted that this isohyetal map differs considerably from previously published maps for the region. The high altitude areas which mark watershed divides and barriers stand out clearly with extremes of 70.5 inches on Mount Washington, elevation 6290 ft, and 51.8 inches at Searsburg Mountain, elevation 2300 ft. In the lowland and river valley areas, rainfall diminishes from 46 inches on the coast to a 34-inch isohyetal in the rain shadow of Mount Washington at approximately 500 ft. The increases in rainfall with elevation were compared with the formula by Barrows and a very good comparison obtained.

Let us consider an application of the map of mean annual precipitation for studies of storm rainfall particularly in mountainous areas. On the West Coast where precipitation is largely orographic, the frequency and amount of precipitation have been predicated on the assumption that storm patterns are similar to the mean annual-precipitation pattern by the United States Engineers and LINSLEY [1947]. In New England the position of major centers of storm precipitation is largely due to frontal action, but in mountainous areas the distribution of storm rainfall is governed by both frontal and orographic effects. Storm rainfall is thus subject to the normal influences of distance from the source of moisture, elevation, and rain shadow effect, the same factors which affect annual rainfall. At a specific location, the storm precipitation may be considered to be, first, the result of the frontal action in a general storm pattern and, second, the effect of local factors such as the orographic effects and distance from the source of moisture. If precipitation records in a general storm are expressed as a percentage of mean annual or seasonal precipitation a fairly constant index of the general storm rainfall is obtained regardless of exposure or altitude of the station. This method has proved quite useful in extrapolating the rainfall for storms of record and developing storm rainfall in mountainous areas of the Connecticut and Merrimack River basins.

Acknowledgments--This work was done under the direction of G. R. Williams who was formerly in charge of Reports and Hydrology, Division Office, Corps of Engineers. The flood-control work in the New England Division is under R. G. Moses, Division Engineer, with J. E. Allen and H. J. Kropper in charge of engineering. Runoff data were furnished and reviewed by H. B. Kinnison, District Engineer of the United States Geological Survey. Precipitation data were available from the records of the United States Weather Bureau and the Massachusetts Department of Public Health [GOODNOUGH, 1930; and WHITE, 1942 and 1943] and various power companies. It should also be noted that this work is an application and extension in the use of data and principles developed by others, rather than an original development.

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BENDING AND SHEAR TESTS ON LAKE ICE

James T. Wilson and John M. Horeth

Abstract--This paper reports the results of bending and shear tests made on ice from Lake Michigan and on artificial ice so frozen as to have the same crystal orientation. The bend specimens normally failed in tension with an indicated tensile strength of about 200 psi. A marked increase of tensile strength with decreasing temperature was indicated. The shear strength was found to be about 100 psi. No temperature coefficient for shear strength could be detected. Specimens of the ice were studied in polarized light. It was observed that the optic axes of the ice crystals were usually normal to the surface of refrigeration. The crystal diameters were usually less than one inch.

Introduction--Even though a great deal of work has been done on the physical properties of ice and the literature is filled with references [BARNES, 1926; and DORSEY, 1940], relatively little information has been accumulated on the strength of lake ice. Work by BROWN [1926] on the bending strength and by FINLAYSON [1927] on the shearing strength of river ice furnished the only comprehensive data found in a rather intensive search of the literature. A summary by WEINBERG [1938] presents some useful data but it was impossible to examine the original references for most of the information.

The work described here was financed by the United States Coast Guard through Contract N6-232, Task order VI of the Office of Naval Research, and the tests were guided by their interest in ice-breaking.

Method--Tests were performed on specimens of artificial ice so frozen as to have the same crystal orientation as natural lake ice and also on specimens of lake ice picked up from the United States Coast Guard Cutter Mackinaw in northern Lake Michigan. All of the specimens were sawed out with ordinary wood saws having six to ten teeth per inch. None of the surfaces was polished and where possible the upper and lower surfaces of the ice sheet were left as surfaces of the test specimens. Most of the beams used for the bending tests were from 2 1/2 to six inches in height, 2 1/2 to five inches in width, and from 15 to 30 inches in length. Some of the specimens of lake ice were of larger cross section. The specimens tested in shear were usually approximately 2 1/2 inches square and six inches long.

The blocks of artificial ice from which specimens were cut were frozen in wooden trays padded on the inside with excelsior or sponge rubber so that the expansion on freezing would not distort the block of ice. The padding was separated from the water by an inner membrane of thin sheet rubber. The trays were large enough so that several specimens could be cut from each block. Samples of the artificial ice were examined in polarized light and their crystal structure found to be very similar to that of the natural lake ice.

In both the bending and the shear tests the specimens were broken in a testing machine built for these experiments. Two four-inch I-beams approximately three ft in length were held parallel and one above the other by adjustable tie rods. A hydraulic jack fitted with a gage to read the oil pressure on the ram was attached to the bottom I-beam. For the bending tests two adjustable wooden bearing blocks were fitted to the lower surface of the upper I-beam and two more to a cross head on the ram of the jack. The extremities of the beam rested against the upper bearing blocks and the jack forced the two lower supports upward. This subjected the beam to pure bending. The supports were so positioned that the beams failed in tension in the span between the lower blocks. All of the beams tested were arranged with the surface of refrigeration horizontal, that is, with the optic axes of the crystals in the direction of the applied forces.

For the shearing tests a special shearing tool was constructed to be used in the press described above. The upper surface of the specimen rested against two rectangular wooden blocks faced with brass plates and separated by approximately three inches. The lower surface of the specimen was forced upward by a rectangular brass-faced wooden block fitted to the ram of the jack. This block was of a size and so positioned that it would just pass between the upper blocks. The specimens were all arranged as for the bending tests with the optic axes vertical.

For both bending and shearing tests the applied force was read from the hydraulic gage on the jack. The jack and gage system were calibrated against an accurate test machine.

It was realized that the rate of loading might influence the results, although the work by BROWN [1926] had not indicated this to be the case for bending. It was impossible to make the rate of loading uniform but an attempt was made to carry each test to rupture in a time of one to three minutes. Bending tests made over much longer intervals (50 min) indicated that the rate of loading was not a critical factor.

The experiments on artificial ice were carried out in a refrigerated room in which the temperature remained constant to within a few degrees. Because of other experiments that were in progress in the room it was undesirable to raise the temperature to 32°F. To obtain data at this temperature the specimens were removed from the refrigerator and allowed to warm up and then taken back in and broken within a very few minutes. Temperature measurements indicated that this introduced no significant error.

The tests on lake ice were carried out on the United States Coast Guard Cutter Mackinaw during the latter part of January 1948. Specimens were obtained over the side and prepared and broken on deck.

The main sources of error are thought to reside in the measurement of the applied force and in the measurements of the specimen dimensions. These errors could easily amount to five per cent. However, the strengths of individual specimens varied so much from the average that it was not thought necessary to try to increase the accuracy of the measurements.

Results of strength tests--The results of the bending tests are presented in Table 1 and Figure 1. The data obtained by Brown in tests on ice from the St. Lawrence River are included. Each point in Figure 1 represents a single specimen.

Table 1--Results of bending tests

Investigator	Ice	Temperature	Number of specimens	Average strength	Range
		°F		psi	psi
Wilson and Horeth	Artificial	32	11	180	126-266
Brown	St. Lawrence	28-30	12	184	126-306
Wilson and Horeth	Lake Michigan	12-20	6	214	151-270
Brown	St. Lawrence	14-16	12	214	177-311
Wilson and Horeth	Artificial	-9	9	256	226-296

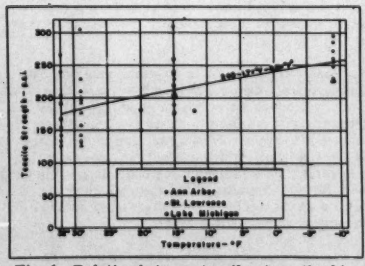

Fig. 1--Relation between tensile strength of ice and its temperature

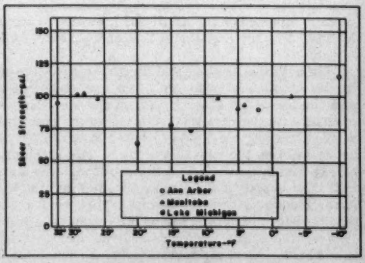

Fig. 2--Relation between shear strength of ice and its temperature

The data indicates a relation between the tensile strength and the temperature of the form: Tensile strength = 240 - 1.7 × °F - 0.01 X (°F)^2. The accuracy to which the coefficients are determined is very low.

The specimens of lake ice were typical of the full thickness of the ice sheet. In some cases a beam including the full thickness was broken and in other cases the thickness was divided into two beams. The lake ice usually had a cloudy zone up to two inches thick in the upper portion. The total thickness was about one foot. The cloudy zone did not seem to cause appreciable weakening of the beams.

The results of the shear tests are presented in Table 2 and Figure 2. The data obtained by FINLAYSON [1927] for river ice are included.

Table 2--Results of shearing tests

Investigator	Ice	Temperature	Number of specimens	Average strength	Range
		°F		psi	psi
Wilson and Horeth	Artificial	32	10	94	41-161
Finlayson	River	29	..	101	.....
Finlayson	River	28	..	102	.....
Finlayson	River	26	..	98	.....
Wilson and Horeth	Lake Michigan	12-20	13	75	39-103
Finlayson	River	8	..	99	.....
Finlayson	River	5	..	91	.....
Finlayson	River	4	..	94	.....
Wilson and Horeth	Artificial	2	10	90	58-120
Finlayson	River	-3	..	101	.....
Wilson and Horeth	Artificial	-10	10	115	70-173

The points plotted in Figure 2 are averages. Finlayson gives only averages and states, "Each coordinate point represents the average of many tests." He does not give the range for each temperature but does state that the maximum value found was 353 psi which indicates a range somewhat greater than ours.

It will be noted that the average for lake ice is lower than for the artificial or river ice. The 13 specimens of lake ice represent four different vertical sections through the ice sheet. For three of the sections a specimen was cut from the top, middle, and bottom of the sheet. For the fourth section an extra middle specimen was cut. If the upper specimens which usually included cloudy ice are not included the average becomes 84 psi.

Finlayson remarks that artificial ice is only about 80 per cent as strong as natural ice. However, he does not state how his artificial ice was frozen.

Crystal size and orientation--It is well known that ice crystallizes in the hexagonal system and that in natural lake and river ice the crystals are usually arranged with the optic axes vertical [DORSEY, 1940]. However, a careful search of the literature furnished almost no information as to the size of the crystals. It was considered desirable to keep the cross section of all the test specimens several times larger than the crystal diameters. For this reason the crystal size and orientation were studied.

Sections of both the lake ice and the artificial ice were examined in polarized light. Sections about four inches square and 1/4 to 1/2 inches thick were cut parallel to the surface of refrigeration and examined by placing them between ten-inch discs of polaroid. The vibration directions of the polaroid discs were crossed at right angles and the system illuminated from behind. In this manner the crystal diameters and the approximate orientation of the optic axes could be determined easily.

Figures 3 and 4 are photographs of two sections of lake ice cut from a vertical prism extending from the top to the bottom of a 12-inch thick ice sheet. Figure 3 shows a section from near the top but below the cloudy ice and Figure 4 shows a section about two inches up from the bottom. A number of such prisms were sectioned and in every case the crystals were larger in the bottom of the sheet. Very few sections examined showed crystals more than one inch in diameter.

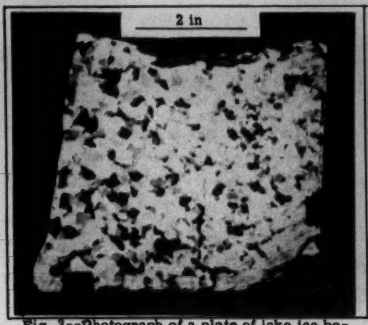

Fig. 3--Photograph of a plate of lake ice between crossed polaroids; section cut parallel to surface just underneath the cloudy top part of the ice

Fig. 4--Photograph of a plate from same prism as 3, but about two inches from and parallel to the bottom surface of the ice

The crystal diameters in the artificial ice were usually about 1/2 inch. The diameter was usually quite uniform from bottom to top. It is thought that there was nothing so different in the size or orientation of the crystals in the lake and artificial ice as to cause any significant difference in their strengths.

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REPORT OF THE CHAIRMAN OF THE SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF OCEAN BASINS, 1947-1948

H. H. Hess, Chairman

During the past 18 months there has been greater activity in geophysical research at sea than in any previous period. It is not the purpose of this report to summarize the accomplishments of this research, but rather to point out problems which have arisen and which are in urgent need of solution to permit further general advances.

As a result of the work of Petterssen, Ewing and Hersey, and Ewing with various collaborators on the Mid-Atlantic Ridge Cruise, a large number of measurements of depth to the first reflecting layer below the ocean floor have been made. These depths have a considerable factor of uncertainty, since the speed of the seismic waves through the ocean-bottom materials is not known. It thus becomes very important that some refraction seismic work be done in the deep-sea to obtain the necessary constants to convert the observed time intervals into true depths.

While the investigators themselves have been most careful to point out that they are measuring depth to the first reflecting layer, many geologists seem prone to push the conclusion one step farther and consider the results as indicating the total thickness of sediments on the ocean floor. This is quite unwarranted at the present time, since it is possible that highly reflecting layers would be intercalated with deep-sea sediments. Such layers might result from past differences in the ocean in temperature or chemical composition, so that limestones or chemical precipitates might be present in the sections or they might be due to lava flows. The presence of thin reflecting layers could be deduced from refraction seismic work, since they would have little effect on the refracted waves even though they had given strong reflections.

The investigation by Koning of shear directions of one deep focus earthquake in the East Indies has led to a whole series of interesting speculations on deep focus earthquakes in general and on possible infracrustal convection currents and their directions of flow. This appears to be such a fertile field for obtaining basic information of deep magatectonic processes that it seems most important that a number of deep focus earthquakes at various depths be similarly investigated.

The expanded program of gravity observations at sea on the United States Navy Submarines by Ewing, Worzel, and their colleagues has resulted in a great accumulation of observation data which has quite outstripped the means of computing the data and applying the various corrections. The investigators are confident that the computational bottleneck will be overcome shortly.

The extraordinarily interesting and important results which have come from the Bikini investigation, drilling, seismic, and magnetic data, may be supplemented by further deep drilling this year. While undoubtedly the most important objective is to determine the nature of the structure under the atoll, its history, and the rock types of which it is composed, very important additional information could be obtained by thermal investigations in the hole. The rate of heat loss and thermal gradients beneath the oceans are at present completely unknown quantities. The drill hole presents an excellent opportunity to get at least some information on these quantities. Hypotheses on the cooling of the Earth are today based entirely on data from continents. Loss of heat from the ocean floor to sea water is also of considerable interest to oceanographers.

This report was sent to each Committee member, and comments were received from the following: F. P. Shepard, W. H. Bucher, M. Ewing, R. H. Fleming, C. S. Piggot, H. T. Stetson, J. B. Hersey, and E. B. Roberts. A brief abstract of some of these comments is given below. The Chairman has discussed orally some of the subjects of the above report with the three remaining members of the Committee, R. Gunn, D. C. Skeels, and George Woollard.

Shepard--Makes reference to numerous fathograms now being received and the possibility of subdividing the ocean floor into physiographic and tectonic provinces. Also mentions the rounded cobbles and terraces found on Erben and Twin Banks by Navy electronics vessel.

Ewing--Has comments similar to Shepard's, plus note that one refraction profile in the deep sea showed that the first reflecting layer was not a thin intercalated layer in oceanic sediments. Expects to make more profiles this summer. Also mentions abundant evidence of life shown by photographs in depths exceeding 1000 fathoms.

Fleming--Stresses importance of work of the Swedish Expedition on the Albatross.

Piggot--Comments on necessity of solving problems brought up by the first reflecting layer with respect to total amount of deep sea sedimentation and mentions seriousness of problem of accumulation of data on oceans much more rapidly than it can be processed. Stresses need for data on thermal gradient under oceans.

Stetson--Points out that possible tidal correlations are more significant when only deep focus earthquakes are considered than when earthquakes are considered indiscriminantly. Also considers possible means of making thermal measurements in oceanic areas.

Hersey--Comments on seamounts in Atlantic.

Roberts--Alldredge's 1948 paper at the American Geophysical Union meeting discussed an anomaly found by magnetic airborne detector on a flight in the Pacific Ocean area. The particular significance would seem to be that this illustrates a great need for comprehensive absolute surveys. Dean Carder of the United States Coast and Geodetic Survey has evidence of a 160-km discontinuity through seismic studies in the Pacific, which is perhaps worthy of mention.

The recording of strong water-borne sound waves from distant earthquakes may be of interest. Seismologists in the United States Coast and Geodetic Survey were believed first to notice this very remarkable effect of long-distance transmission of sound waves of seismic origin in the SOFAR layer. Ewing, he understands, is conducting special investigations of this effect. This subject could be advanced by having more short-period instruments of high magnification at oceanic stations.

In connection with the work of Koning, it might be well to note the work of Byerly and Japanese seismologists, who used the compression-rarefactional characteristics of P-waves to study focal displacements of normal shocks, and of Neumann who developed a rule which uses the direction of the S-wave ground motion to determine the horizontal direction of focal shearing.

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PROGRESS OF THE EUROPEAN TRIANGULATION ADJUSTMENT

Floyd W. Hough

Abstract--A report on the progress of the readjustment of the European network of triangulation is presented. After completion of the Central European triangulation readjustment, the Commission on the Adjustment of European Triangulation studied proposed plans for extending the readjustment project to include all of Europe west of 32° east longitude, and recommended a two-phase plan of procedure, whereby a preliminary adjustment by the improved Bowie Junction Method (to be made as soon as possible) would be followed eventually by a classical readjustment of all data available.

The First International Geodetic Conference on the Adjustment of European Triangulation was held August 7, 1946, at Paris, France. This conference was called by the International Association of Geodesy to meet coincidently with the assembly of its Permanent Commission. At the conclusion of the conference, the members of the Permanent Commission adopted unanimously a resolution setting up the Commission on the Adjustment of European Triangulation to operate under the direction of the Chairman of the Triangulation Section of the International Association of Geodesy. The Commission is made up of geodetic engineers from each of those countries adhering to the International Union of Geodesy and Geophysics who are territorily involved in the adjustment. Representation was extended by courtesy to the United States. The Commission was charged with the duty to examine fully the triangulation adjustment problem of Europe, both from technical and operational standpoints, and to make a comprehensive study of the proposal to extend the then current Central European Adjustment to include all of Europe on a common geodetic datum. It was directed to report its findings and recommendations to the General Secretary of the International Association of Geodesy.

The first plenary session of the Commission on the Adjustment of European Triangulation convened at the call of its chairman on October 15, 16, and 17, 1947, in Paris, France, following ten months of intensive study and personal contacts on the part of various members of the Commission. The following 12 nations were represented: Great Britain, France, Holland, Belgium, Switzerland, Denmark, Sweden, Finland, Italy, Poland, Czechoslovakia, and the United States. A number of papers were presented covering the technical, operational, and political phases of the subject.

The United States announced the completion in June 1947, of the Central European First-Order Triangulation Adjustment which embraced an area of 1,100,000 sq km [HOUGH, 1947]. This adjustment had been begun in June 1945, shortly after the United States Army had captured the German town of Friedrichsroda in the Province of Thuringia. The head of the Trigonometrical Section of the Reichsamt für Landesaufnahme, together with a number of his geodetic engineers and mathematicians, was transferred by military order to Bamberg, Germany, in the United States occupation area. An adjustment of the first-order triangulation of the so-called Greater Reich was nearing completion at that time. However, upon examining the methods used in this adjustment, it was found that the Germans had been required by expediency to adjust the control piecemeal, block by block, without inclusion of bases and Laplace azimuths. They, themselves, admitted the inadequacy of such an adjustment and stated that the geodesists had not been permitted to exercise their judgment in the matter.

The German technical unit was set up in Bamberg and directed to proceed immediately on a readjustment, by least squares, of the Central European area and to employ the Bowie Junction Method with certain improvements over that used in the 1927 adjustment of the first-order triangulation of the United States. A network of arcs, generally along meridians and parallels, was selected from the existing area triangulation. German records of the past 140 years were carefully examined and evaluated in order to use in the adjustment the most logical values for the astronomic and angle observations, the bases, and Laplace azimuths. All base measurements were reduced from the German Legal Meter to the International Meter as the standard of length. The numerous astronomic stations in the network provided a means for the almost complete elimination of the error due to the deflection of the plumb line, while the inclusion of a large number of Laplace azimuth stations corrected the twist which is bound to occur in the extension of arcs of triangulation.

The completion of the Central European Adjustment (see Fig. 1), involving the solution of 1305 condition equations, resulted in the fixing in geographic position of 714 first-order triangulation stations in that area. All were in correct mathematical relationship to each other on a common

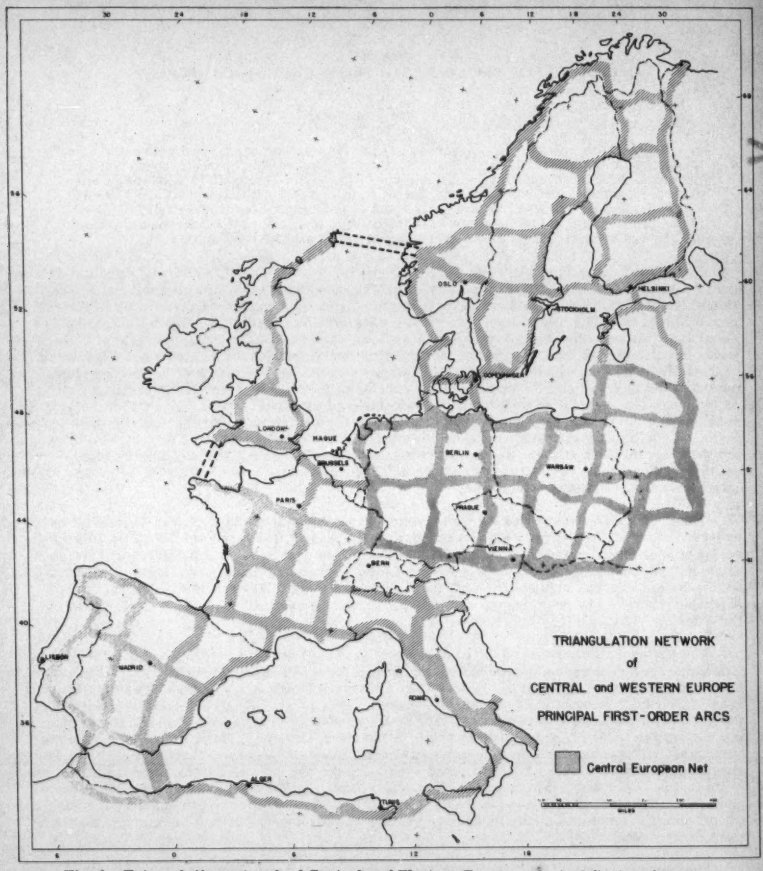

Fig. 1--Triangulation network of Central and Western Europe principal first-order arcs

geodetic datum and computed on the International Ellipsoid which was recommended for adoption by the Madrid Conference of the International Association of Geodesy in 1924. Interior triangulation of the area can be adjusted at will to this rigid framework much as the inner portions of a modern steel building are fitted to its network of beams and columns. Since there is a known tendency in a least square adjustment of this type for the corrections to be forced outward, a double chain of figures was employed along the entire perimeter, at the suggestion of the United States Coast and Geodetic Survey, thus furnishing a strong outer ring which might be held fixed in any extension of the adjustment to contiguous areas.

Following the report of the delegate from the United States on the completion of the Central European Adjustment and his proposal that the facilities of the German mathematical group at Bamberg be employed to extend this adjustment to include all of Europe on a common geodetic datum, the Commission listened to several learned speakers on the general subject of adjusting the remaining geodetic control of the continent. There was definite agreement on the very great desirability of bringing all of Europe to a common datum, but there was evident also a pronounced reluctance on the part of most of those nations who had suffered under German invasion to permit the German group at Bamberg to handle the newer first-order triangulation data of their countries. This intense feeling prevailed even though it was pointed out that the work would be under the administrative control of the Chief Engineer of the United States Forces in the occupied area and that the technical details would be guided by a technical staff made up of one geodetic expert from each of the countries. While absence of the consideration of national security in this handling of first-order control was recognized, national pride would not permit the geodesists of a nation so recently a powerful enemy to enjoy the prestige of carrying on a project of such scope and importance, and directly affecting those countries whom Germany had wronged.

The question was raised as to the adequacy of the improved Bowie Junction Method for an adjustment which should give the ultimate refinement required for a most accurate scientific study of the figure of the Earth. It was readily admitted that a classical simultaneous adjustment involving thousands of equations would be a more ideal method but at the same time less practical from the standpoint of personnel, time, and cost. It was suggested that the final desired result be reached in two phases or operations: (1) The proposed junction adjustment which would involve angle, side, length, latitude, and longitude equations, the employment of Laplace azimuths and of the existing observed astronomic values of latitude and longitude; (2) the application of computed isostatic and gravity corrections to the observed astronomic positions, and the reduction from geoid to spheroid, followed by a classical readjustment of the entire area to a more refined geodetic datum.

The two-phase system of adjustment, which was approved by the Commission, has the distinct advantage that the first phase will eliminate in a reasonably short time the numerous datums on several different spheroids and the disparities now existing at the national boundaries; also, that changes resulting from the second phase, while most precise for the ultimate scientific purposes desired, may be completed at leisure over a period of years and in the end cannot differ greatly from the results of the first phase. This compromise solution proved to be satisfactory both to those who desire an early consistent mathematical adjustment of the European triangulation on a common geodetic datum and to those who are interested in the ultimate perfection of the adjustment.

On the third day of the conference the Commission adopted a resolution which expressed the intention of extending the Central European Adjustment under the direct control of the International Association of Geodesy and with employment of the two-phase method of operation just mentioned. Provision was made for a sub-commission of approximately five geodetic experts which would further explore the problem and report to the Commission as a whole at the 1948 Assembly at Oslo, Norway.

In view of the strong feeling on the part of the western nations that German engineers should not be employed on any adjustment involving use of the newer first-order triangulation data of those countries and the admitted likelihood of a long delay in carrying on such an adjustment without an adequate existing central group of personnel or adequate funds to set up such a group, the representative from the United States proposed informally that the International Association of Geodesy should sub-let to the Army Map Service the first phase of the adjustment. This adjustment would be made in Washington at no cost to the Association and would be subject to inspection by designated representatives of the International Association during the progress of the work. Each participating country would be expected to furnish to the Army Map Service a complete list of observed directions prepared from its latest first-order triangulation observations, its bases, Laplace azimuth, astronomic latitude and longitude observations, descriptions of stations, together with a technical report on the data with recommendations as to its use in the adjustment and relative weights to be accorded. The second phase of the adjustment, involving isostatic and gravity corrections to the astronomic positions, would be done by the Isostatic Institute at Helsinki in later years or through such other arrangements as the International Association might determine.

This plan whereby the first adjustment would be done in Washington met with the immediate approval of the Secretary of the Association who agreed to submit it for ratification to the nations involved as soon as the official offer was received. The Chief of Engineers later approved the plan, and it is at present under consideration by the western countries. The Army Map Service

has contracted provisionally with the United States Coast and Geodetic Survey to proceed with the adjustment without delay if the plan is accepted.

There are in the neighborhood of 1500 first-order stations contained in the extended network of the proposed first phase of the triangulation adjustment in Western, Northern, and Southern Europe. Some 3000 equations must be solved. The United States Coast and Geodetic Survey has agreed to complete the adjustment within 18 months of receipt of the checked lists of directions and pertinent data covering the area. If concurrence is forthcoming, the Army Map Service plans to have the lists of directions ready to submit within a few weeks after the receipt of data.

The successful completion of the proposed extension of the first-order triangulation of Europe, and later that of the Balkans area, will be the realization of the hopes of European geodesists for many decades, including those of our revered friend and eminent scientist, General Georges Perrier, who served for many years with high honor and esteem as Secretary General of the International Association of Geodesy. The mathematical adjustment on a common geodetic datum of the high quality first-order triangulation of Europe will not only remove the many troubling disparities in surveys at the international boundaries of that continent, but will contribute immeasurably to scientific studies of the figure of the Earth, which, after all, is the basic quest in the Science of Geodesy.

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Army Map Service,
Washington 25, D. C.

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PROGRESS IN GEODETIC SURVEYS BY THE UNITED STATES COAST AND GEODETIC SURVEY FROM JULY, 1947 TO JUNE, 1948

J. H. Brittain

Abstract--The principal work engaged in by the Division of Geodesy of the United States Coast and Geodetic Survey during the period July 1, 1947 to June 30, 1948, has been concerned with the extension of geodetic control surveys (vertical and horizontal) for large-scale flood-control and reclamation projects of the United States Corps of Engineers and the United States Bureau of Reclamation, and for mapping by the United States Geological Survey and the United States Forest Service. The triangulation and leveling have been undertaken in the order of priorities established by these organizations. In addition, some triangulation and leveling have been done in Alaska, in earthquake regions of California, on city-survey projects, and on special projects for the Armed Forces. Eight triangulation parties and eight leveling units have worked throughout the year. Four other triangulation parties and two leveling units worked through the summer and fall of 1947, but were disbanded when weather conditions made a continuation uneconomical. Two of the latter triangulation parties and three leveling units were reorganized in May to operate through the summer season of 1948.

The area of principal interest to the Corps of Engineers at the present time is the Missouri River Basin. Two triangulation parties and one leveling party of three units continued through the summer and fall of 1947. About May 1, 1948 four triangulation parties and one leveling party of three units resumed work in the area. During the past year work was completed in the Gasconade River area in Missouri and along the Blue and Nemaha Rivers in Nebraska and Kansas. Work is in progress along the main stem of the Missouri River between Rulo, Nebraska, and Bismarck, North Dakota, and in the vicinity of Fort Peck, Montana, and along the Pomme de Terre and Marias des Cygnes Rivers in Missouri and Kansas.

Two triangulation parties and one leveling party of three units operated through the summer and fall of 1947 in Indiana in areas of interest to the United States Geological Survey. One of the triangulation parties resumed work in June of this year in the northern part of the State. A unit from one of these triangulation parties executed triangulation in the vicinity of McClure, Ohio, to establish points for use in connection with the calibration of the nine-lens camera of the United States Geological Survey.

The parties working in the Missouri River Basin and in Indiana during the summer and fall of 1947 were assigned to projects in the southern states for the winter. These included triangulation and leveling in the Trinity River Basin of Texas, triangulation in Oklahoma near Lawton, southern Mississippi, and North Carolina, and leveling in the Chattahoochee River area in Georgia and Alabama.

In the western part of the United States four triangulation parties and one leveling party of three units have operated throughout the year. Projects were completed in central Utah, near Tucson, Arizona, in central Washington west of the Pasco, in the Mt. Hood National Forest area, and along tributaries of the lower Columbia River. A number of projects now under way, or left incomplete on account of parties moving to mountainous regions for summer work are leveling in Washington, Idaho, California, and Arizona, and triangulation in northern California, western Arizona, and Nevada.

One of the projects undertaken during this past year was that of reobserving triangulation between Bakersfied, California, and the Coast, thence north along the Coast to north of San Francisco. These observations will be the basis for the study of Earth movements due to earthquakes in this region.

A triangulation party worked in Alaska during the summer months of 1947 and returned to the area in May 1948. Triangulation was completed in the Cook Inlet area and along Tok Cutoff between arcs of triangulation along the Richardson and Alcan Highways. First-order leveling also was executed along Tok Cutoff. The party presently is engaged in executing triangulation along the north shore of Bristol Bay.

Urban survey projects undertaken on a cooperative basis with North San Francisco Bay cities, California, and the city of Cincinnati, Ohio, were completed during the year. The Coast and Geodetic Survey furnished the supervisory personnel and instruments and made the office computations. Less skilled personnel, transportation, and miscellaneous supplies were furnished by the local organizations.

A number of small projects involving the establishment of horizontal and vertical control for special uses by the Armed Forces were undertaken during the year. Horizontal control was established in the vicinity of Annapolis and Baltimore, Maryland during the summer of 1947 for use in connection with the proposed construction of a bridge across Chesapeake Bay. This party was later combined with one of those operating in Indiana.

In July 1947, a triangulation party was organized to extend control into the iron ore region of northern Minnesota. This project was not completed in the fall of 1947 before adverse weather conditions made it necessary to disband the party. The project is being completed in 1948.

Astronomic observations for latitude, longitude, and azimuth were made along arcs of triangulation in Indiana, Missouri, Utah, Oregon, Washington, Arizona, and Texas for use in the adjustment of triangulation. The Bamberg broken telescope was used for the latitude and longitude observations. The astronomic observatories at Ukiah, California, and Gaithersburg, Maryland, maintained for study of the variation of latitude, were continued throughout the year.

Gravity observations were undertaken about April 1 in eastern Oklahoma and Kansas. This work consists of establishing both pendulum and gravimeter stations in areas not covered by the various oil and geophysical prospecting companies to provide data for use in connection with a study of the deflection of the vertical from gravity anomalies.

Base lines were measured at frequent intervals along the schemes of triangulation to control the lengths. Invar tapes were used for this purpose, their lengths being determined by the United States Bureau of Standards before and after the base measurements.

All triangulation provided during the year has been of first-order or modified second-order accuracy. The modified second-order is only slightly below first-order, the same instruments and methods being used but with maximum triangle closures of five sec being allowed to cut down on reobservations. The latter has been confined entirely to break-down for supplemental stations or area triangulation tied rigidly to first-order at frequent intervals. The Parkhurst first-order theodolite was used almost entirely within the United States. The Wild theodolite, on account of its light weight, was used in Alaska where transportation of personnel and equipment was by aircraft. This instrument gave excellent results, the average triangle closure on the project along the north shore of Bristol Bay being 0.65 sec.

United States Coast and Geodetic Survey,
Washington 25, D. C.

(Manuscript received July 2, 1948 amended to cover fiscal year; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 23, 1948; open for formal discussion until May 1, 1949.)

Transactions, American Geophysical Union Volume 29, Number 6 December 1948

REPORT OF THE COMMITTEE ON THE CHEMISTRY OF NATURAL WATERS, 1947-1948

L. V. Wilcox, Chairman

Wm. W. Aultman	C. S. Howard	Norris W. Rakestraw
A. P. Black	Wm. L. Lamar	Melvin Romanoff
M. M. Ellis	Stanley W. Lohman	C. S. Scofield

In the list of members of the Committee published in Transactions in December 1947, page 966, the name of Melvin Romanoff was inadvertently omitted.

A wide range of interests is represented by the membership of the Committee. Lohman is Chairman of the Research Committee on Ground Water of the AGU and his participation on the Committee on the Chemistry of Natural Waters should tend to coordinate the activities of the two Committees. Among the other interests expressed by committee members are corrosion of metals underground, chemistry of surface and ground waters, pollution problems, softening and treatment of natural waters, oceanography, conservation, geochemistry, and agricultural uses of water.

Investigational work by members of the Committee is in progress in many of the fields mentioned above. S. W. Lohman is in charge of cooperative ground-water work in Colorado and Wyoming and is personally making a study of the geology and ground-water resources of the Grand Junction artesian basin in Mesa County, Colorado. M. Romanoff is engaged in corrosion studies involving field tests of metals and alloys to determine the effects of chemical composition of soluble constituents of soils. This is a part of an investigation by the National Bureau of Standards, started in 1922, the results of which have recently been assembled in a single publication entitled, Underground Corrosion, Circular of the Bureau of Standards C-450. W. L. Lamar is studying the chemical character of the surface waters of Georgia, North and South Carolina, and Virginia. W. W. Aultman has under investigation a number of interesting problems. He is studying the behavior of synthetic, siliceous zeolites and synthetic resin ion exchangers in the base exchange softening of natural waters. Other studies involve the corrosive effect of softened natural waters, the reclamation of lime from water-softening sludges, and the electrochemical removal of anions and cations from water.

C. S. Howard, formerly Chairman of this Committee, is continuing his work on the surface waters of the Colorado River, Rio Grande, and Columbia River Basins. In addition to chemical studies he is giving considerable attention to the suspended sediments and is studying methods for determining particle size distribution and the effect of solutes in the waters on the settling rates of the sediments. A. P. Black, of the University of Florida, recently accepted the chairmanship of a committee to make a state-wide survey of salt-water intrusion and ground-water levels together with certain associated problems and prepare a report by December 1948. Earlier he served as special consultant to the Florida State Committee on Natural Resources. This Committee held public hearings and prepared legislation looking toward a program of state-wide conservation and control. He presented a paper at the meeting of the American Water Works Association in San Francisco last July entitled, Basic Concepts in Ground-Water Law. The Chairman, L. V. Wilcox, is primarily interested in agricultural uses of water. Studies are in progress on the quality of irrigation and drainage waters, the effect on plants of boron in water or in soil, and soil changes that result from irrigation. A paper presented by the Chairman at the summer meeting of the American Water Works Association was entitled, Agricultural Uses of Reclaimed Sewage Effluent.

During the summer of 1947, conferences, held in Washington, led to a recommendation by the Inter-Departmental Committee on Hydrology relative to the method of reporting electrical conductivity measurements. The Committee suggested that all Federal agencies standardize on the microhom per cm as the unit for reporting conductivity measurements of waters. Many agencies, including the Quality of Water Branch of the United States Geological Survey, the United States Bureau of Reclamation, the International Boundary and Water Commission, the United States Regional Salinity and Rubidoux Laboratories adopted the suggestion effective October 1, 1947.

A sub-committee of the Inter-Departmental Committee on Hydrology is assembling a set of analytical procedures suitable for the analysis of natural waters for irrigation purposes.

The time between the appointment of the Committee on the Chemistry of Natural Waters and the preparation of this report was too short to plan and complete any important project. Several projects have been suggested for future consideration and one has been definitely agreed upon, that is, a study of methods of collection of samples of water. Such questions as the following will be considered: (1) Purpose for which water samples are collected; (2) selection of sampling site; (3) volume of sample; (4) frequency of collection; (5) method of compositing; (6) method of preservation; (7) type of container; (8) list of determinations regularly made; and (9) volumes required for each determination.

A short bibliography of interest in the field of water chemistry is attached as Appendix 1.

APPENDIX 1

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Rubidoux Laboratory,
Riverside, California

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Transactions, American Geophysical Union Volume 29, Number 6 December 1948

REPORT OF THE RESEARCH COMMITTEE ON RUNOFF, 1947-1948

C. C. McDonald, Chairman

C. R. Hursh	W. C. Ackerman	W. T. Wilson
B. S. Barnes	G. A. Hathaway	W. U. Garstka
E. S. Cullings	R. W. Davenport	H. L. Cook

Since 1946, the Committee has given consideration to terminology as related to the field of runoff. As the science of hydrology develops, there is increasing need for a more definite and uniform terminology in order to promote use of more precise language in technical literature. While it may not be possible or desirable at this time to standardize completely, it appears entirely possible to standardize many of the terms in common usage. This Committee has begun a compilation of letter symbols and terms related to runoff.

The activities of various organizations in the field of runoff during the year are summarized by members of the Committee as follows:

Walter T. Wilson (U. S. Weather Bureau, San Francisco, California)--During 1947 the United States Weather Bureau continued expansion of its river forecasting activities. The forecast centers established at Cincinnati, Ohio, and Kansas City, Missouri, began actual flood-forecasting operations, while new centers were established at Tulsa, Oklahoma, for the Arkansas Basin, and at St. Louis, Missouri, for the middle Mississippi River and tributaries. All centers are continuing the preparation of forecasting techniques following basic plans determined after extensive investigations by the Bureau's Procedure Development Section in Washington.

In the Western States new centers have been established at Portland, Oregon, and Salt Lake City, Utah, for water-supply forecasting. These centers took over issuance of forecast bulletins for the 1947-1948 year and are continuing development of procedures for additional areas.

The Corps of Engineers-Weather Bureau cooperative snow investigations are described in the current report of the Research Committee on Snow. Inquiries may be addressed to the Program Director, South Pacific Division, Corps of Engineers, Oakland Army Base, Oakland, California.

G. A. Hathaway (Office, Chief of Engineers, Washington 25, D. C.)--In addition to routine investigations of runoff necessary to preparation of reports and to planning and operation of flood control and river and harbor projects, the Corps of Engineers is carrying on the following special investigations which may be of interest.

(1) A comprehensive program of snow investigations was organized in 1945 in cooperation with the United States Weather Bureau. The three snow laboratories organized under this cooperative program are continuing the study of the influence of snow on the planning, design, and operation of flood control and river and harbor projects. Processing and analysis of the data are being carried on concurrently and technical reports based thereon are being prepared.

(2) The Louisville District of the Corps of Engineers has been carrying on an investigation of rainfall-runoff relationships for sewered areas on the Beargrass Creek drainage basin and four sewered areas at Louisville, Kentucky. The investigations were initiated in 1944 for the purpose of developing methods for computing design-storm discharges from the Beargrass Creek area and typical sewer systems for pumping plant design. Discharge records for nine areas, varying in size from 60 ac to over 50 sq mi have been collected. Precipitation data from 18 recording and two non-recording rain gages are available. Unit hydrographs and other techniques for computing discharge records have been utilized in analysing the basic data.

(3) Following is a brief resume of the airfield-drainage investigations being carried on by Division and District Offices of the Corps of Engineers:

(a) Ohio River Division surface-runoff studies--An investigation of the surface-runoff characteristics of typical airfield areas including both turfed, paved, and combination areas. Rainfall and runoff observed at 15 stuided areas at four airfields in the Ohio River Basin. Drainage areas vary from 0.7 to 682 ac. Basic data and analysis published in Report on Drainage Verification at Military Establishments, available from the District Engineer, Louisville, Kentucky.

(b) Surface-drainage studies, Pinecastle Airfield, Florida--An investigation of surface-runoff characteristics of six typical airfield-drainage areas representative of the high intensity rainfall and uniform sand, sub-grade conditions characteristic of Florida. Drainage areas vary from 4.0 to 10.0 ac. The field observations have been completed and the basic data are in progress of analysis.

(3) Surface-drainage studies, Santa Monica, California)--An investigation of runoff resulting from both natural and simulated rainfall on various types of surfaces common to airfield construction. Simulated rainfall tests will be conducted on lengths of flow up to 500 ft and on both paved, turfed, and bare cover conditions and at various slopes. Construction of test sections is complete and pilot tests are being initiated using simulated rainfall.

(d) Surface- and subsurface-drainage studies, Fort Ruckman, Massachusetts--An investigation of surface and subsurface runoff on natural soil with turf cover and prepared turfed base courses simulating turfed runway areas. Areas are 10 to 75 ft in width by 75 to 250 ft in length with 2.0 per cent slope. Automatic recordings are made of rainfall, surface and subsurface runoff, and temperature. Periodic measurements made of soil moisture and turf cover. Collection of field data and analysis of records continuing.

(e) Subsurface-drainage studies, New England Division--A comprehensive study of subsurface flow through pavement base courses and of combined surface and subsurface flow in open french drains. The investigation includes a detailed review of the theory of subsurface flow through base courses, model studies using viscous flow between closely spaced glass plates, full scale field-test sections, and flow observations on existing subsurface-drainage systems. Also included are rainfall and runoff observations for combination-drainage systems at three airfields. Initial data published by New England Division in Subsurface Drainage Investigation 1945-1946, Comprehensive Report.

(f) Mole-drainage investigation, New England Division--An investigation of the possible application of the principle of the mole drainage to airfield and construction drainage problems. Studies to date include a comprehensive review of foreign and domestic use of mole drains in agriculture and laboratory studies of methods for providing a structural lining for the mole drain to prevent its collapse on non-plastic soils.

(g) Drainage-structure model investigations, St. Paul District--An investigation at the Hydraulic Laboratory of the University of Iowa of the hydraulic characteristics of gutters and drain inlets common to airfield construction. Laboratory tests completed and final report in preparation.

(h) Arctic- and subarctic drainage studies, St. Paul District--An investigation of hydrology associated with drainage of military installations in arctic and subarctic areas. Work being conducted by the University of Minnesota under the supervision of the Permafrost Division, St. Paul District. Studies in initial stage with no field work as yet.

(i) Electrical-drainage studies, Washington District--An investigation of electro-osmosis and associated phenomena as a means of accomplishing drainage of non-gravitational water from airfield foundations. Study involves a detailed review of related foreign and domestic investigations, laboratory, and large scale model studies, and prototype-field installations to determine the design and effectiveness of electrical drainage methods.

C. R. Hursh (Southeastern Forest Experiment Station, Asheville, North Carolina)--The effect of forest-land management on runoff is being investigated by the Branch of Research, U. S. Forest Service, in the important headwater areas of the southern Appalachian Mountains. The Coweeta Experimental Forest is now being operated by the Southeastern Forest Experiment Station as an outdoor hydrologic laboratory. This 5000-ac area lies within the Nantahala National Forest in Macon County, North Carolina, at an elevation of 2200 to 5200 ft. The sharply defined drainage pattern, deeply weathered Archean country rock, and a 70-inch annual rainfall occurring on the area are favorable for experimental watershed studies.

The immediate practical objective of the runoff studies in progress is to establish a scientific basis for practical watershed management. Investigations have been carried out since 1933 to determine changes in streamflow following different types of land management. Studies are in progress to determine the effect of reduction in the density of the forest stand, the effect of clearing and cultivating steep mountain slopes, and the effects of grazing, fire, and logging on water yield and water quality. Hydrologic records have been taken at a total of 30 weir-gaging stations, 80 rain-gaging stations, and 26 observation wells.

The effects of land management on stream flow are being evaluated in terms of all phases of the water cycle as measured before and after different land treatments have been applied. Turbidity and water quality are also being studied as they are affected by land use. Differences in stream discharge before and after changes have been made on the watershed are compared statistically on the basis of runoff variables. In addition, it has been found possible to use a second watershed as a control to check year by year climatological differences during the entire period of observation. A number of technical reports have been published on these analyses, several of them appearing in the Transactions of the American Geophysical Union.

The stream regimen brought about by different land-use treatments is also being studied by the use of graphical comparison of flow-frequency-distribution curves during and after treatment periods. Comparison is made with stream-flow frequencies on control areas as a check on climatological differences between the before and after treatments. Parameters obtained graphically from the curves are also being compared.

H. L. Cook (U. S. Department of Agriculture, Washington 25, D. C.)--As the Soil Conservation Service is not directly represented on the Committee, I have obtained information on current activities in the field of runoff research from technicians of that agency.

The so-called runoff studies of the Soil Conservation Service were initiated in 1938, and by 1939 measurements and observations were being made on some 100 small-drainage areas at 26 locations throughout the United States. During the War, field work was considerably curtailed but the analysis of the records proceeded as rapidly as possible. At the present time only two sets of watersheds, located near Edwardsville, Illinois, and Fennimore, Wisconsin, remain in operation.

The comprehensive experimental-watershed studies of the runoff process were initiated during the middle thirties at three sites near Coshochton, Ohio; Hastings, Nebraska; and Waco, Texas. The War made it necessary to halt research work at the Waco Watershed. It was also found necessary to suspend publication of the Hydrologic Bulletin series of USDA publications in which the results of the Experimental Watershed research were released. During 1947 it was found possible to reopen the Waco project, but it is still necessary to operate with a very restricted staff. Limitation of funds has made it impossible to resume publication of the Hydrologic Bulletin.

From the soil conservation experiment stations, much valuable information on the runoff and erosion from small areas, mainly plots, has been collected at these stations, some of which have been in operation more than 15 years. Stringent reductions in appropriations have curtailed research on these stations and only a few of them remain in operation.

R. W. Davenport (U. S. Geological Survey, Washington 25, D. C.)--The surface-water investigations of the United States Geological Survey continued during the year. Discharge records are currently being obtained at more than 5800 locations in the nation-wide network, as well as in Alaska and Hawaii. Publication of the basic records of runoff in Water-Supply Papers was continued. Notable among the special and analytical reports released during the year are the following: W. S. P. 915, Major Winter and Nonwinter Floods, New York and Pennsylvania, by W. B. Langbein and others; W. S. P. 968A, Flood runoff in Willamette Valley, Oregon, by M. D. Brands; W. S. P. 968B, Floods of the Puyallup and Chehalis River Basins, Washington, by I. E. Anderson; W. S. P. 968C, Topographic Characteristics of Drainage Basins, by W. B. Langbein and others.

Studies of methods of extending stream-flow records by comparison with long-term stream-flow stations and by correlation with precipitation and other records were continued.

A compilation of reservoirs in the United States of 5000 ac ft or more has just been published by the Geological Survey. Computations of monthly and annual normals of stream flow were carried forward and substantially completed at about 120 gaging stations used as representative stations for the Water Resources Review.

A study of the magnitude and frequency of floods in the Columbia River Basin above the Snake River was completed during the year.

Reports on local floods, giving the results of field investigations of rainfall and discharge were made by the United States Geological Survey in Ohio. (The flood of June 1946 in Wayne and Holmes Counties, Bull. 9, Ohio Water Resources Board.)

U. S. Geological Survey,
Tacoma 2, Washington

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REPORT OF THE COMMITTEE ON PHYSICS OF SOIL MOISTURE, 1946-1947

L. A. Richards, Chairman

G. B. Bodman Don Kirkham W. O. Smith
Willard Gardner S. J. Richards F. J. Veihmeyer

In continuance of a custom, the chief effort of the Committee during this period has been the preparation of a symposium on an aspect of the physics of soil moisture. A paper was prepared by F. J. Veihmeyer and A. H. Hendrickson entitled The Permanent Wilting Percentage as a Reference Point for the Measurement of Soil Moisture, which was sent to various reviewers for comment and discussion. This paper, with the discussions, is published elsewhere [see pp. 887-896] in this issue as a contribution of this Committee.

REPORT OF THE COMMITTEE ON LAKES, 1947-1948

P. E. Church, Chairman

George Benton C. S. Howard N. Allen Riley
J. L. Hough G. E. Hutchinson R. R. Woolley

Few matters have come before this committee for consideration this past year. One reporter for one of the questions asked at the last meeting of the Limnology Commission of the International Union of Geodesy and Geophysics has completed the answer.

The greatest activity has been centered on the Great Lakes. Through the cooperation of the Woods Hole Oceanographic Institution and the United States Lakes Survey, United States Corps of Engineers, about a dozen core samples, four to eight ft long, were obtained from the bottom of Lake Huron. These samples are being analyzed in the Geology Department at the University of Illinois.

Investigation of various other phases of limnology, both physical and biological, are being conducted by universities, and by state and governmental agencies. Each of these is working on a particular small-scale problem. There is a lack of coordination between these investigations; there is no coordinated effort of either investigators or plans. It has come to the attention of the Committee that there are two or three plans which are rather comprehensive in scope, more comprehensive than any institution or agency is working on at present; any of these plans could readily be carried out. If one were adopted by all who are interested and there were pooling of resources and additional equipment, and funds for additional man power were obtained, it would be possible to realize returns of better character than at present.

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DISCUSSION OF

"PRECISE LEVELLING ON THE ALASKA HIGHWAY" by R. H. MONTGOMERY

[Trans., v. 29, pp. 13-16, 1948]

George O. Guesmer (Corps of Engineers, St. Paul, Minnesota)--This article presents valuable data on the methods and work done. Of particular interest to the writer was the description of the various types of bench marks used, as well as the difficulties encountered with certain specific installations.

In connection with studies of permanently frozen ground conducted by the Corps of Engineers in Alaska, a rather detailed investigation was made to obtain a simple type of bench mark stable enough to be used for a permanent marker. This is a difficult problem in an area subject to freezing and thawing cycles. The presence of a layer of permanently frozen ground at depths of two to ten ft from the ground surface introduces another factor into the general problem of obtaining a stable bench mark. In the study made by the Corps of Engineers, pipe bench marks were placed in the ground at depths varying from two to 40 ft. Elevations of the bench marks were referred to a bench mark established on a well casing 240 ft deep which extended through the active zone of from five to seven ft from the ground surface and subject to the freezing and thawing cycles, a permafrost zone of approximately 150 ft, and thence into unfrozen sand and gravel.

Observations of the bench marks over a period of three years resulted in the following conclusion. Stable vertical control points or bench marks may be obtained by placing pipe to a depth of 18 to 20 ft below the ground surface to insure a length of pipe in the permafrost at least equal to twice the thickness of the active zone of the ground. In placing a vertical control point, care must be taken to avoid areas where the permafrost table may be affected by heated buildings. The bench mark may be placed in the permafrost in the case of frozen silt by thawing a small hole with a prospector's steam boiler or by using a churn or core drill; in the case of heavy gravel, it would be necessary to use a churn drill. This type of bench mark will not require any particular insulation, or care in its maintenance. The pipe may project above the ground at least one foot and may be slotted at the lower end to permit the fluid thawed material to flow into the pipe and make a more stable structure when the ground freezes back. Freezing will take from ten days to a month or more, depending upon the season of the year. It is suggested that, where possible, bench marks be placed on a deep well casing using a welded bracket or other point permanently attached to the well casing.

DISCUSSION OF

"INDUCED INFILTRATION OF RIVER WATER TO WELL" by RAPHAEL G. KAZMANN

[Trans., v. 29, pp. 85-89, 1948]

Raphael G. Kazmann (Ranney Method Water Supplies, Columbus, Ohio, Author's closure)--Anderson's comments are practical and valuable and bear out Rorabaugh's words of caution. Anderson points to a practical difficulty in applying the theory and presents the proper solution.

Rorabaugh's example of flow under a river is possible if artesian conditions exists, as, for example, in the 400-foot sand at Memphis which extends under the Mississippi River into Arkansas and which is separated from the river by several hundred feet of tough clay. The hydraulic gradients on the Arkansas side are toward the river and on the Tennessee side, away from the river, towards the areas of pumpage in Memphis. However, this is an artesian and not a water-table condition. Rorabaugh applies the term free water table for use in referring to what is generally known as water table, and uses water table for the generally accepted term piezometric surface. The writer believes that the comment is the result of a difference in nomenclature rather than a difference of opinion.

It is to be expected that more complex situations than that at Mt. Pleasant will be encountered; the experience at Louisville bears this out. The Mt. Pleasant instance was deliberately selected

because it was such a perfect text-book example and illustrated the theory in an excellent fashion.

Rorabaugh's ideal test which might take months or years is probably not practical except for purposes of intensive study. As a basis for construction it is, under most circumstances, impractical to conduct a test of more than a week's duration. However, careful attention to the types of material encountered combined with water-level observations during non-pumping conditions yields invaluable information, and may, occasionally, shorten the required pumping period to two or three days.

Rorabaugh's equation (1) is very useful as an analytical check of a graphical solution. It suffers from the same defects as the graphical method: Until the observation wells have been drilled and the natural slope of the piezometric surface has been determined, the angle ϕ is not known. However, the analytical solution afforded by (1) will prove to be a useful tool for the ground-water hydrologist.

Rorabaugh's figures, which indicate that pumping tests yield results in which the transmissibility and distance to line of recharge adjust themselves, are of great interest. It is indeed instructive to compare computed specific yields of wells on the basis of some of these figures: When a = 2000, T = 159,000; when a = 385, T = 117,000.

Assuming an infinite aquifer on the land side, the quantity, Q, obtained from a well after a steady state of flow is reached, is as follows: $Q = 2\pi T\, s/2.3 \log_{10}(2a/r_w)$.

Where Q is the discharge in gpd, T is the transmissibility in gpd/ft, s is the drawdown at the well in ft, a is the distance to the line of recharge in ft, r_w is the effective radius of the well in ft. For s = 1 and r_w = 50, Q_1 = 226,000 gpd, and Q_2 = 268,000 gpd.

Therefore, the error introduced by using the maximum distance to the line of recharge obtained from the pumping test is about 16 per cent, on the conservative side if a perennial water supply is required, or 16 per cent on the unsafe side if a system of relief wells designed to handle the computed quantity of water for the purpose of insuring the stability of a levee is involved.

This example illustrates the need for understanding the limitations of formulas before applying them to ground-water problems.

The discussers point to other methods of discovering whether a river is recharging an actively pumped aquifer. Such methods include temperature changes [JEFFORDS, 1945; MEINZER, 1946; KAZMANN, 1947] changes in chemical quality [JEFFORDS, 1945], a comparison between dewatered volumes of aquifer and the volume of water pumped during a given period [ENGLER, THOMPSON, and KAZMANN, 1945], and changes in the storage coefficient, S, during a pumping test [KLAER and KAZMANN, 1943]. There are numerous interesting and vexing problems connected with the infiltration of river water to aquifers, as, for example, the rate of percolation through a river bed under varying conditions of flow, head, and temperature.

The preceding paragraph is intended merely to outline a few of the many problems which were purposely ignored in the original paper in order to present a basic principle with as few distractions as possible.

Corrigendum--The following correction is noted in the discussion of this paper as published. Equation (3) on page 91 should read $s_1 = \left\{2.30\, Q \log_{10}[(2a + r_1)/r_1]\right\}/2\pi T$.

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LETTER TO THE EDITOR

SUGGESTED LIST OF TOPICS FOR A TEXTBOOK ON APPLIED HYDROLOGY

During the past 15 years, the science of hydrology has developed to that stage where there is general agreement on the basic facts and principles. The time is ripe and the needs call for the issuance of a new text book on hydrology, its fundamentals and its application in engineering and agriculture. It would be a textbook for teachers and students in colleges of engineering and agriculture. This book should have the simplicity and condensed strength of its predecessors; the works of Adolph F. Meyer and Daniel W. Mead.

The author or editor-in-chief should be one experienced in teaching and one familiar with the evolution, theories, and accepted facts, as well as all of the trials and errors which have served their purpose and are not now suited to the proposed book.

A word on the practical and financial side: It is the writer's opinion that there is a large field for the sale of a textbook on modern applied hydrology and that the income would assure a good publisher and give a fair financial return to the authors and editors.

The Section of Hydrology, AGU, could furnish a major and indispensable service if each of its research committees would review the published articles on hydrology within its domain and mark those excerpts, passages, or paragraphs which the committee approved as correct and useful for inclusion in such a textbook.

Similar advice, and with approved references or excerpts for engineering applications, could be made by the Hydrology Committee of the American Society of Civil Engineers. The American Society of Agricultural Engineers could materially aid in the large field of hydrology applied to agriculture.

Definitions in the textbook should be in accord with the Glossary of Hydrology prepared by Thorndike Saville and his co-workers. The Physics of the Earth, Vol. IX, Hydrology, by O. E. Meinzer, is a treatise invaluable for the teacher and much of it would be useful in a proposed textbook. The papers by that eminent hydrologist, the late Robert E. Horton, furnish a standard for clarity and conciseness in scientific expression.

The suggested outline follows:

PART 1

Elements of hydrology

(1) Rainfall--Average annual; average monthly; storm rainfall, seasonal, heavy, maximum possible; intensities, totals for one day, two days, and longer; rain-storm data of United States Weather Bureau; Sharpe and Holton's method; Theissen's areas.

(2) Snow--Average annual distribution; snow surveys; runoff yield and forecast.

(3) Infiltration--Phenonema of soils; soil moisture, voids, gravity water, and capillary water; local and basin infiltration capacity; ultimate or constant infiltration capacity; mass infiltration curves.

(4) Runoff--Runoff equals rainfall minus infiltration; phenomenon of surface runoff, stream flow, base flow; United States Geological Survey Water-Supply Papers, depletion curves, turbulent and laminar flow; hydrographs of runoff, rain simulators; Theissen's areas applied to runoff depths.

(5) Estimated surface runoff and stream flow--Storage, the storage equation; runoff volume equals volume of infiltration minus volume of storage in a given interval of time; stream velocity versus wave velocity; yield of surface water from observed data; yield by basin analogy; estimates

by rational method; logical evaluation of C from infiltration data; limits in assumed uniform rainfall; unit hydrograph method.

(6) Transposition of storms.

(7) Elements of statistical analysis for rainfall or floods.

(8) Ground water--Flow, surface, root, and ground-water zones; infiltration, evaporation, and transpiration; drawdown cones; deep wells.

(9) Physics of soil moisture--Bouyoucos soil-moisture measurements and other soil moisture-meters.

PART 2

Applications of hydrology to engineering

(1) Water-supply storage, ground water.

(2) Water power, storm sewers, culverts, and bridges.

(3) Flood control.

(4) Land drainage.

(5) Airport drainage.

(6) Spillway design

(7) Factors of safety.

(8) Flood frequency economics and insurance.

(9) The engineer's work relates principally to floods and the major factors of runoff.

PART 3

Hydrology applied to agricultural practice

(1) Irrigation.

(2) Land drainage.

(3) Increasing soil moisture.

(4) Contour plowing.

(5) Vegetal cover.

(6) Supplementary ground water.

(7) Runoff reduction.

The agricultural engineer, in making economic comparisons, has to deal with a large amount of detailed analysis not required by structural engineers.

The text involving the foregoing table of contents should include a description of instruments such as rain gages, snow-survey apparatus, stream gages, lysimeters, flow meters, soil-moisture apparatus, infiltrometers, and other items of equipment.

This textbook is not simply descriptive and qualitative. It should include ample figures for quantitative use in practice of application or design.

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NOTES AND PERSONALIA

NOTES

Submarine-gravity expeditions--The U. S. S. MEDREGAL, G. H. Whiting commanding, sailed from Key West, Florida on May 25, 1948, for the measurement of gravity at sea. One hundred and seventeen gravity observations were made on profiles from Alligator Rocks to Cay Sal Bank, from Cay Sal Bank to the Bahama Banks, from Miami to Gun Cay, and from Jupiter Inlet, Ponce de Leon, Charlestown, and Frying Pan Shoals to sea. The cruise was completed on June 11, 1948, at Philadelphia, Pennsylvania. This expedition was arranged with the cooperation of the Office of Naval Research, Navy Department, and Commander Submarine Force, U. S. Atlantic Fleet.

The U. S. S. Capitaine, L. R. Vasey commanding, sailed from San Diego, California, on August 18, 1948, for a four-month expedition for the measurement of gravity at sea from San Diego to Hawaii to Australia to Guam to Okinawa and back to Hawaii. This expedition has been arranged with the cooperation of the Office of Naval Research, Navy Department, and Commander Submarine Force, U. S. Pacific Fleet. The scientific observations on these cruises are being made by C. L. Drake. The gravity observations are being made with a Vening Meinesz pendulum apparatus and a Bell Telephone Laboratories crystal chronometer, loaned by the Woods Hole Oceanographic Institution. Additional observations of wave pressures are being made with a sensitive pressure meter loaned by the Naval Ordnance Laboratory, to observe the relationship of wave motions to the disturbances of the pendulum apparatus.

The observations along the East Coast of the United States completes a network of gravity observations over the continental margin from Maine to Cuba. These observations coupled with those on land of G. P. Woollard will make this coast one of the best regionally surveyed areas in the world. The observations in the Pacific will commence a program of reconnaissance surveying of the Pacific Ocean, as well as a detailed study of the relations of gravity anomalies to the earthquake epicenter belts.

This work is part of a two-year program of gravity observations at sea, sponsored by the Office of Naval Research. J. Lamar Worzel is in charge of the project, under the direction of Maurice Ewing of Columbia University.

Program for scientists holding reserve commissions--The Department of the Army has established a program for those who have reserve commissions and who are scientists, including geophysicists, the objectives of which are (1) to maintain useful affiliation of such persons with the Organized Reserve Corps, (2) to provide peacetime Reserve assignments that will enable optimum utilization of education, experience, and skills of such officers, (3) to furnish mobilization assignments best adapted to their talents, and (4) to prepare these officers for mobilization. The program provides that training be in keeping with the scientific interests and competence of the officers rather than the traditional kind of training in which scientists normally have little interest, but is to be implemented only in those areas where there is substantial local interest. The program is under the direction of the Research and Development Group, Logistics Division, General Staff, U. S. Army, and is described in Army Circular No. 127. Inquiries about the organization of a group or assignment to a group should be made to the Unit Instructor or Senior Army Instructor of the Organized Reserve in the locality where the officer resides.

Reserve commissions for scientists--The Department of the Army has established a plan for the commissioning of reserve officers who have scientific competence in various aspects of geophysics and certain other sciences, the grades ranging from second lieutenant to colonel. No previous military experience is required. Full details of the program are provided in Army Circular 210 which may be secured from local Reserve Unit Headquarters, Organized Reserve Unit Instructors, Army Headquarters in New York, Baltimore, Atlanta, Chicago, Houston or San Francisco, or from the Adjutant General's Office in Washington.

New Chinese Journal of Geophysics--Volume 1, number 1 of the Journal of the Chinese Geophysical Society, dated June 1948, has arrived in the United States. It contains nine papers by Chinese scientists, eight in English and one in German, and cover a wide field of subjects, five in terrestrial magnetism. Bibliographic items of these papers will be found in the bibliography in this issue.

Earthquakes, May to August 1948--The United States Coast and Geodetic Survey, cooperating with Science Service, the Jesuit Seismological Association, and a selected group of widely scattered seismological stations, has located provisional epicenters during this period as shown in Table 1.

Table 1--Provisional epicenters of the United States Coast and Geodetic Survey

Date	Time U. T.	Epicenter		Approx. Depth	Approx. mag.[a]	Remarks
		Lat.	Long.			
1948	h m	°	°	km		
May 28	5 36.2	12 S	77 W	...	6 3/4 - 7	Near coast of Peru
June 15	11 44.7	33 1/2 N	136 E	...	7	Near southern coast of Honshu, Japan, slightly deeper than normal
June 18	00 53.9	6 S	155 E	...	7	Solomon Islands region, possibly deeper than normal
June 21	12 05.4	3 N	126 E	...	.....	Celebes Sea
June 27	12 48.3	17 N	85 W	...	7	Off north coast of Honduras, slightly deeper than normal
June 27	21 39.2	56 N	158 W	...	.....	South of Alaska Peninsula
June 28	7 13.5	36 N	136 1/2 E	...	7 1/4	Near west coast of Honshu Island, Japan, heavy casualties and severe property damage reported from Fukui area
June 29	10 28.5	16 S	172 W	...	7 1/4	Samoa Islands region
June 29	16 06.5	43 N	47 E	...	.....	Caucasus region, near western shore of Caspian Sea
June 30	12 21.2	38 1/2	20 1/2 E	...	.....	Ionian Sea near west coast of Greece, casualties and property damage reported from Island of Lerkus and nearby mainland
July 7	02 19.1	33 N	136 E	...	6 1/2	Off southern coast of Honshu Island, Japan, reported felt south of Osaka
July 8	12 34.6	71 N	6 W	...	.....	Near Jan Mayen Land
July 14	22 28.9	4 S	142 E	...	6 1/4 - 6 1/2	New Guinea
July 15	11 02.0	10 N	104 W	...	6	Pacific Ocean 550 mi off SW coast of Mexico
July 16	7 12.5	14 1/2 N	92 W	100	6 1/4	Near coast of Guatemala
July 16	7 19.7	14 1/2 N	92 W	100	6 3/4	Near coast of Guatemala
July 19	22 26.3	15 N	91 1/2 W	...	.....	Near coast of Guatemala, possibly deeper than normal
July 20	11 02.4	17 S	74 1/2 W	100	7 1/4	Off coast of SW Peru
July 22	20 05.4	49 1/2 N	130 1/2 W	...	.....	Off west coast of Vancouver Island
July 22	20 52.7	49 1/2 N	130 1/2 W	...	.....	Off west coast of Vancouver Island
July 24	06 03.2	35 N	24 E	...	6 1/2	Near SW coast of Crete
July 31	19 04.2	7 N	82 W	...	.....	Off SW coast of Panama, shocks on July 28 at $14^h21.8^m$ and $15^h05.6^m$, probably from same source, reported to have damaged buildings on Coiba Island
Aug. 7	14 40.2	39 N	142 E	...	.....	Off SE coast of Honshu Island, Japan
Aug. 11	10 36.2	17 1/2 N	95 1/2 W	50	7	Southern Mexico, reported felt in in state of Vera Cruz
Aug. 19	13 50.8	62 N	151 W	100	6 1/4	South-central Alaska
Aug. 19	19 59.0	5 N	82 W	...	6 1/2	South of Panama
Aug. 25	06 09.4	24 S	63 W	...	7 1/2	Salta Province, Argentina, possibly slightly deeper than normal
Aug. 27	16 48.4	25 S	68 W	...	.....	Western Argentina
Aug. 28	02 27.8	57 N	161 E	...	.....	Kamchatka
Aug. 29	17 37.8	15 1/2 S	171 W	...	6 3/4	Samoan Islands region, felt at Apia
Aug. 29	18 36.4	16 1/2 N	107 W	...	.....	Off coast of Mexico

[a]Magnitudes reported by the Seismological Laboratory, Pasadena, California.

Civil Service examination for meteorologists--The U. S. Civil Service has announced an examination for meteorologists, grades P-2 to P-5 to close June 30, 1949. Inquiry covering this unassembled examination should refer to announcement 117 and be addressed to the U. S. Civil Service Commission, Washington 25, D. C.

PERSONALIA

Stewart H. Folk has resigned his position as Technical Advisor to the Officer in Charge, Naval Petroleum No. 4 and has accepted the position of Associate Professor of Geology at Baylor University.

Maurice A. Garbell, President of Maurice A. Garbell Inc., Aeronautical Consultants, has been retained as consultant by Transocean Air Lines to direct the technical and scientific activities of the Air Force-Navy-Civil Landing Aids Experiment Station at Arcata, California.

Joseph B. Hammon of Sacramento, California has accepted an assignment of the Department of State for work on the completion of the soils and land classification in Paraguay, and interpreting the findings in terms of settlement and agricultural development.

William A. Longacre of the Physics Department of the Michigan College of Mining and Technology has been promoted to the rank of full professor. He will continue his work as consulting geophysicist for mining companies in the United States and Canada, and is currently undertaking such work for the Cleveland-Cliffs Iron Company.

Athelstan F. Spilhaus, Professor of Meteorology and Oceanography, and Director of Research, New York University, has been appointed Dean of the School of Technology, University of Minnesota.

Harrison W. Straley, III, consulting geological engineer and geophysical engineer, has accepted a professorship in geology at the University of Oklahoma. He devoted most of the summer in Oklahoma on a survey of the mineral resources of the eastern half of the State, sponsored by the Public Service Company of Tulsa and Oklahoma A and M College.

Theodore von Karman was recently awarded the 1948 Franklin Medal of the Franklin Institute for his outstanding work in American jet plane research.

Charles R. Hedke, hydraulic engineer with the Corps of Engineers in Omaha, Nebraska, died March 11, 1948. He was born in Milwaukee, Wisconsin, March 24, 1878 and received his baccalaureate degree in civil engineering from the University of Wisconsin in 1900. He devoted the major portion of his professional career to private practice and consulting work in the service of various industrial companies on water problems. In 1942 he began his services with the Corps of Engineers which continued until his death.

Emil G. Reimann, hydraulic engineer with the Soil Conservation Service stationed at the University of Illinois, died March 31, 1947 at the age of 42. He was born in Germany, and received his baccalaureate degree from the University of Illinois in 1932, and had been with the Soil Conservation Services since 1938 on research work on soil and water relations, collection of runoff data, and the design of stock ponds and other small reservoirs.

Frank Rieber, head of the Rieber Research Laboratory in New York, died suddenly on June 30, 1948. He was born in Placerville, California, in 1891, and received his baccalaureate degree in physics from the University of California in 1915. His early professional work was devoted to development and invention of X-ray equipment. In 1923, he became head of his own organization in the development and use of refraction and reflection seismic surveying. Since 1941, he has been engaged in the development of new methods of geophysical exploration. He was inventor and developer of numerous instruments for geophysical work, and the holder of many patents.

Ralf R. Woolley, hydraulic engineer with the U. S. Geological Survey died suddenly on July 1, 1948. He was born at Paris, Idaho, September 13, 1884. He received his baccalaureate degree in mining engineering from the University of Utah in 1909. His early professional career was devoted to miscellaneous engineering work and to teaching. In 1917 he entered the service of the United States Geological Survey on water resources investigations, which work he continued until his death. He had been a member of AGU since 1934.

UNION, SECTION, AND COMMITTEE ACTIVITIES

Report of Committee on Audit for Fiscal Year, July 1, 1947 to June 30, 1948

A. G. McNish (Chairman), R. H. Weightman

Your Committee on Audit has examined the books of the Union for the fiscal year ending June 30, 1948, and found them in agreement with the financial statement as prepared by the General Secretary's Office and shown below. The cash balance on hand as of June 30, 1948 was $17,006.60 after deduction had been made for checks outstanding in the amount of $3,143.45. This includes the balance of the Robert E. Horton Fund in the amount of $3,531.41 and the William Bowie Medal Fund in the amount of $133.30, which funds are not available for the regular operating expenses of the Union. The expenditures and receipts of the Union are carerully and accurately posted and supported by vouchers. The Committee calls attention to the fact that in addition to the cash balances, the Union owns Series F Government Bonds with a maturity value of $3,200.00, which were purchased for $2,368.00.

Your Committee wishes to point out that when allowance is made for Bills Receivable and Payable and for Investment, valued at cost, the net balance of the Union exclusive of equipment held is $24,412.20 as compared with $22,769.73 on June 30, 1947.

Your Committee again wishes to commend the office of the Executive Secretary for the excellence of the state of the books which, as in the preceeding years, were found to be in perfect shape

Financial Statement, Fiscal Year, July 1, 1947 to June 30, 1948

Cash assets and receipts		
Cash balance, July 1, 1947, as reported from June 30, 1947		$17,943.39
American Geophysical Union	$13,782.86	
William Bowie Medal Fund	146.10	
Robert E. Horton Fund	4,014.41	
Dues, 1945-1949 et seq		22,265.67
1945	$ 9.00	
1946	142.00	
1947	4,688.71	
1948	17,198.29	
1949 et seq	227.67	
Sales of publications		5,593.82
Transactions	3,728.70	
Reprints	1,850.12	
Exhibit maps	15.00	
Miscellaneous contributions		35.73
Grants		3,400.00
Geological Society of America	3,000.00	
National Research Council	400.00	
Payments under $2,500.00 RDB Contract		1,250.00
Total ($17,943.39 + $32,545.22)		$50,488.61
Disbursements		
Transactions (3 1/2 numbers of 1947, 3 numbers of 1948[a])		$10,164.60[a]
Reprints		1,582.78
General expenses, Office of the Union		13,981.97
Salaries	$11,277.23	
Equipment	422.57	
Stationery and miscellaneous	1,323.73	
Postange and express	958.44	
General expenses, account of RDB Contract		2,426.25
Salaries	1,867.43	
Equipment	129.43	
Stationery and miscellaneous	221.94	
Postage	207.45	

[a]Note that three full issues were paid for of 1948 Transactions, thus 6 1/2 numbers are charged in this statement.

Twenty-Ninth Annual Meeting (1948)		$ 439.44
Regional Meetings		144.83
Sections		5.50
Terrestrial Magnetism and Electricity	$ 4.00	
Hydrology	1.50	
Committees		3,592.19
Executive	258.29	
Membership	2,166.40	
Editorial and Publication	1,167.50	
William Bowie Medal		12.80
Travel		130.65
Robert E. Horton Fund expenditures		483.00
Investment		518.00
Total disbursements (regular Union accounts)		$31,055.76
Grand total disbursements		33,482.01
Cash balance, June 30, 1948		$17,006.60[b]

[b] Riggs National Bank per statement of June 30, 1948 ..... $20,150.05

Less checks outstanding:

No. 2529	2.25	No. 2642	$ 82.27		
2569	2.25	2643	100.33		
2631	5.00	2644	75.00		
2632	75.00	2645	70.93		
2633	75.00	2647	12.00		
2634	75.00	2648	314.10		
2635	75.00	2650	13.95		
2636	5.00	2651	10.20		
2637	75.00	2652	1289.81		
2638	75.00	2653	518.00		
2639	75.00	2654	34.50		
2640	75.00	2655	7.83		
			Total checks outstanding		3,143.45
			Balance June 30, 1948, as above		$17,006.60

Distribution of bank balance

American Geophysical Union, General Fund	$13,341.89	
William Bowie Medal Fund	133.30	
Robert E. Horton Fund	3,531.41	
		$17,006.60

Investments, June 30, 1948

Prior to July 1, 1947, Series F Government bonds, maturity value $2500.00, at cost	$ 1,850.00	
Purchased during fiscal year, Series F Government bonds, maturity value $700, at cost	518.00	
		$ 2,368.00

Bills receivable, June 30, 1948

Publications		$ 478.19
Transactions	$ 267.43	
Reprints	210.76	
Dues		3,575.00
1947 and 1948, 116 members	$ 1,160.00	
1948, 483 members	2,415.00	
Balance due on RDB Contract		1,250.00
Miscellaneous		2.62
Total bills receivable		$ 5,305.81

Bills payable and advance payments, June 30, 1948

Chesapeake and Potomac Telephone Co. (Stationery and Misc.)	$ 10.40	
W. M. Davies (Stationery and Misc.)	6.00	
Joseph R. Goberna (Overpayment)	4.20	
Maden Tetkik Ve Aram Enstitusu, Turkey (Overpayment)	16.50	
Arnold Court (Overpayment)	3.44	
Dues paid in advance	227.67	
Total bills payable		$ 268.21

Recapitulation

Item	Fund			
	AGU General	Bowie Medal	Robert E. Horton	Total
Cash balance	$13,341.89	$133.30	$3,531.41	$17,006.60
Investments at cost	$ 2,368.00	...	....	2,368.00
Bills receivable	5,305.81	...	....	5,305.81
Totals	$21,015.70	$133.30	$3,531.41	$24,680.41
Bills payable	268.21	...	....	268.21
Net balances	$20,747.49	$133.30	$3,531.41	$24,412.20

Cost of equipment owned by American Geophysical Union

One Globe-Wernicke, 2-pedestal, flat-top steel desk, AGU No. 1, 60 × 34 inches	$ 49.18
One walnut flat-top desk, AGU No. 3, 34 × 66 inches, with glass top	95.43
One walnut typewriter desk, AGU No. 3, 34 × 66 inches, with glass top	100.72
One Globe-Wernicke No. 526 TW imitation-walnut desk, 55 in, Dept. No. 99 (recent Government sales price to DTM)	31.51
One General Fireproofing steel typewriter desk, green right pedestal type, 34 × 60 in	113.75
Two steel posture chairs	22.00
One walnut chair	21.50
Oen No. 617 posture chair with olive green finish, genuine brown leather upholstery, Dept. No. 254	7.00
One wood revolving chair, Dept. No. 148	0.00
Two wood typewriter chairs, revolving, Dept. Nos. 31 and 131	0.00
One 18-inch larger primer Burroughs typewriter, serial No. 60A232450	190.80
One 10-inch elite Royal typewriter, serial No. KHM-2076351	100.31
One 11-inch elite Underwood typewriter, serial No. 11-6126347	129.43
One 11-inch elite Underwood typewriter, serial No. 11-6194757	129.43
One Elliott Addressing Machine, model 80, serial No. 102285 B, on stand	315.99
Twenty-seven tray cabinet (Elliott) with short tray, 27 short trays with fronts and 27 short trays with connecting clips	75.71 75.71
Four steel file cabinets from Globe-Wernicke No. 7341, letter size, No. 24 green	193.60
Two 4-inch drawer, 3 × 5 inch steel filing cases (gift)	0.00
One Triner postal scale, 4 lbs by 1/2 oz	16.20
One Arrow stapler	6.75
One costumer, walnut finish	3.50
One costumer, walnut finish	7.60
One 15-inch Eastman trimmer	13.50
One Hallowell 28-inch steel stool, DTM, No. 70	1.00
One three-fold double burlap screen, brown, oak finish	2.00
One three-section open bookcase composed of book sections Nos. 36, 100, and 1 old section without number, and book section top No. 108	1.00
Ten desk trays, walnut finish	14.00
Twelve copies, Manual of Style, University of Chicago Press	32.50
One Klera-desk	3.70
Two Emeralite gooseneck lamps, DTM, Nos. 110 and 117 at $1.00 each	2.00
One white table	1.00
Two pieces Masonite, each 3 ft × 4 inches	0.00
One book rack	1.00
One work table on trestles	3.90
Total cost of equipment	$1,775.73

[Note: The Union has a large stock of Transactions of past years available for sale, but these are carried as without value in the inventory.]

American Geological Institute--The organization meeting of this new Institute was held in Washington, D. C., November 15 to 16, 1948. Eleven national groups having interest in the geophysical and geological sciences have voted to affiliate and were represented. The organization is within the framework of the National Research Council, sponsored by the Division of Geology and Geography of the Council. A. I. Levorsen of Stanford University was elected President, William B. Heroy, consulting geologist and geophysicist of Dallas was elected Vice President, and Earl Ingerson of the U. S. Geological Survey was elected Secretary-Treasurer. The interim directors representing the American Geophysical Union are W. T. Thom, Jr. of Princeton University, and Ernst Cloos of Johns Hopkins University. The other organizations represented in the Institute are Geological Society of America, American Association of Petroleum Geologists, American Institute of Mining and Metallurgical Engineers, Mineralogical Society of America, Society of Economic Geologists, Society of Exploration Geophysicists, Society of Economic Paloentologists and Mineralogists, Sesimological Society of America, Paleontological Society, and the Society of Vertebrate Paleontology.

American Standards Association--Fred Anderegg, AGU representative on the Committee on Photography Z38 of the ASA advises that the latest standards approved by the ASA are as follows:

Z38.1.49-1948, Dimensions for 35 mm magazine film (for miniature cameras), which governs the length of 35-mm film strips furnished in daylight-loading magazines.

Z38.2.6-1948, General-purpose photographic exposure meters (photoelectric type), which is intended to serve as a guide to the manufacturer in designing and testing his product.

Z38.7.5-1948, Methods of testing printing and projection equipment, being a revision of Z38.7.5-1943.

Z38.8.12-1948, Photographic graduates.

Z38.8.17, Method for predicting the permanency of the silver images of processed films, plates, and papers, which specifies a test method for this prediction.

Z38.8.18-1948, Chromium-plated surfaces for ferrotyping, which defines such surfaces and covers both plated sheets and plated drums for ferrotyping.

There are also 24 specifications for photographic grade chemicals.

SPECIAL ANNOUNCEMENTS

Twenty-Third Regional Meeting in Los Angeles, February 4 and 5, 1949--The Twenty-Third Regional Meeting will be held at the University of California in Los Angeles, California, February 4 and 5, 1949. The Sections of Hydrology and Meteorology will meet. Opportunity will be offered for presentation of papers in other fields in a general session that is tentatively planned. Persons interested in the presentation of papers or in some other aspect of the meeting should get into touch with F. J. Veihmeyer, Chairman of the South Pacific Regional Committee of the Section of Hydrology at Davis, California; M. R. Huberty, in charge of local arrangements for the Section of Hydrology, at the University of California in Los Angeles; or Morris Neiburger, in charge of arrangements for the Section of Meteorology, at the University of California in Los Angeles.

Twenty-Fourth Regional Meeting in Denver, April 26 and 27, 1949--The Twenty-Fourth Regional Meeting will be held in Denver, Colorado, April 26 and 27, 1949, jointly with the Western Snow Conference. While the AGU meeting will be essentially one of the Section of Hydrology, related papers will be welcome. The meeting on April 26 will be that of the Western Snow Conference, and on April 27 that of the Section of Hydrology. Persons interested in taking part in the meeting should write to Herbert S. Riesbol, Bureau of Reclamation, Denver, Colorado, in charge of arrangements for the Section of Hydrology, or Ralph L. Parshall, Ft. Collins, Colorado, General Chairman of the Western Snow Conference, in charge for the Western Snow Conference.

Sets of the Transactions of 1939--Since the publication of the list of back Transactions available on pages 78 and 79 of Part 2 of the Transactions of August 1948, a few complete sets of the Transactions of 1939 have been found. These sets will not be broken, but may be purchased at the price listed ($5.75 for the set of our parts).

Thirtieth Annual Meeting, Washington, D. C., April 20 to 22, 1949--Pursuant to the preliminary earlier announcement of the Thirtieth Annual Meeting of the American Geophysical Union on April 20 to 22, 1948 (Wednesday to Friday), arrangements are under way to provide sessions for all Sections, as well as a general session, and joint sessions of two or more Sections. Place this on your agenda and make plans to come.

This announcement is also an invitation for members and others to communicate plans for preparation and presentation of papers. Titles of papers with three copies of the abstract should be sent in at the earliest possible date, and not later than February 20, 1949, advising of the time required (most papers are allowed from ten to 20 minutes) and projection equipment needed. Send abstracts to the office of AGU at 1530 P Street, N. W., Washington 5, D. C., or to the Secretary of the appropriate section, as follows:

Geodesy	Frank L. Culley	U. S. Coast and Geodetic Survey, Washington 25, D. C.
Seismology	Florence Robertson	4349 Forest Park Blvd., St. Louis 8, Missouri
Meteorology	Woodrow C. Jacobs	4302 Kentucky Drive, Bethesda 14, Maryland
Terrestrial Magnetism and Electricity	David G. Knapp	3827 W Street, S. E., Washington 20, D. C.
Oceanography	Richard H. Fleming	Division of Oceanography, Hydrographic Office, Navy Dept., Washington 25, D. C.
Volcanology	Francis G. Wells	U. S. Geological Survey, Washington 25, D. C.
Hydrology	Ray K. Linsley, Jr., or	5517 Glenwood Road Bethesda 14, Maryland
	Ralph N. Wilson (Program Chairman)	3900 Hamilton St., Apt. L302, Hyattsville, Maryland
Tectonophysics	Wilbur S. Burbank	3346 Runnymede Place, N. W., Washington 15, D. C.

Complete manuscripts of papers should be forwarded in triplicate by March 31, 1949, in order that news releases may be prepared. If a paper is written in collaboration, please indicate by whom it will be presented. Arrangements can be made for presentation of papers by authors who are unable to attend the meetings. Advise also whether the paper is being submitted for the program only or whether it is also desired that it be given consideration for publication. (Papers for publication only are also welcome for consideration for the Transactions.)

The Chairman of the Committee on Meetings (J. P. Marble, U. S. National Museum, Washington 25, D. C.) invites suggestions and comments that will be helpful in planning the proposed meeting. Especially invited are comments relating to papers and symposia bearing on more than one section.

Make hotel or room reservations directly with the hotel of your choice as soon as possible. Failing on a first attempt, bear in mind that advance bookings not taken up are cancelled two weeks in advance, so a follow-up request in the opening days of April may bring the desired response. Our meeting is scheduled for the same week as the convention of the DAR in Washington. This has been true for the last two years also, but at no time yet, to our knowledge, has it not been possible to find quarters. Even though no advance reservation has been made, it has been possible to arrange for quarters after arrival in Washington through the Greater National Capital Committee (204 Evening Star Building, Washington 4, D. C., telephone District 3535) but they may find it necessary to direct you to a tourist home.

John Putnam Marble, Chairman,
Committee on Meetings